What have we learned from the Tevatron for the LHC

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with shamelessly stolen slides from too many people to list here

Lessons from Tevatron for LHC:

Lesson 1:

patience…

Outline

- Tevatron: brief history
- physics at hadron colliders
  - particle detection, trigger, reconstruction, …
- QCD lessons
  - pdf's, NLO, NNLO, …
- Flavor lessons:
  - b-physics at hadron collider is possible
- Precision measurements
  - W mass
- Top quark physics
- Advanced analysis: multivariate methods
  - top and higgs
- Will not talk about the new phenomena searches
  - techniques are the same, and no discoveries have been made so far

very important for all theorists and essential for model builders – need to know how the "sausage" is made and how to interpret the data

Practical Details

- Ask questions!
  - makes for better experience
  - gives me feedback what material I need to emphasize

- You will see quite a bit of LHC/ATLAS/CMS pictures here
  - instead of learning details of Tevatron experiments, learn how LHC experiments were designed (in large degree guided by lessons from the Tevatron experience)

Tevatron: 30 year program

- 22 years of operation so far!!

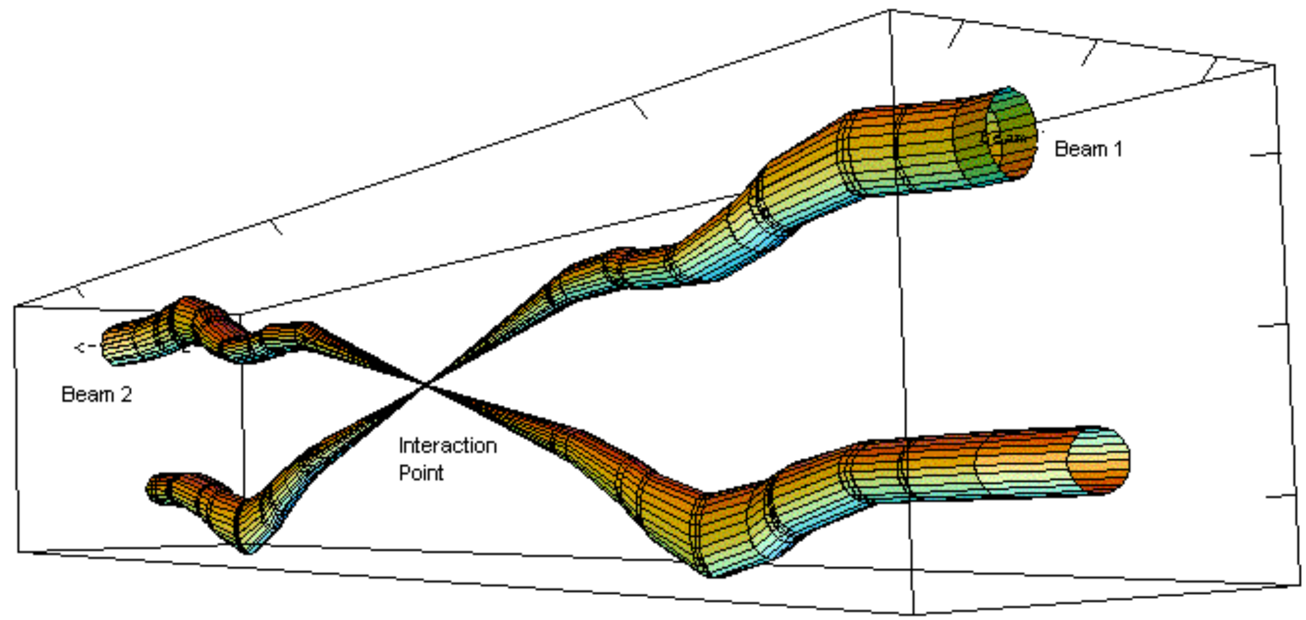
Fermilab 1977

Colliding beams: Tevatron I

- In early 1978 CERN approves the pbar-p colliding beams program in the SPS based on an all stochastic cooling pbar source. The ICE experiment provides the evidence that it can be done. The W and Z will be discovered at CERN in 1983

- in 1979 Fermilab submits a proposal for Tevatron I. Cost $41.5 million without R&D. It appears in the FY81 budget.

Colliding the Beams



Relative beam sizes around IP1 (Atlas) in collision

- At the Tevatron, the interaction region is ~30 microns in diameter and ~27 cm in length

Tevatron I Design Parameters

Luminosity

$$L \sim (N_{pbar} N_p)/(\beta^* (\varepsilon_v + \varepsilon_h))$$

Tevatron Collider Parameters

Luminosity Goal: $L = 10^{30}$ cm^{-2} s^{-1}

Energy: E= 900 GeV $\beta^* = 100$ cm

$\varepsilon_v, \varepsilon_h = 24$ mm-mr $N_p, N_{pbar} = 6 \times 10^{10}$

Number of Bunches/beam: B = 3

Luminosity Lifetime: $T = L(dL/dt)^{-1} \sim 12$ hr

12/20/83

1988-89 Run Statistics

	Design Goal	Achieved 1988-89
Number of bunches/beam	3	6
Number of p's/bunch	6×10^{10}	5.5×10^{10}
Number of $\overline{p}$'s/bunch	6×10^{10}	2.5×10^{10}
B* at BØ [cm]	100 cm	55 cm
$\epsilon_{v,}$ ϵ_H protons [mm-mr]	24	24
$\epsilon_{v,}$ ϵ_H antiprotons [mm-mr]	24	18
Energy [GeV]	900	900
Peak Luminosity [cm^{-2} sec^{-1}]	10^{30}	2×10^{30}
Initial Luminosity Lifetime [hr]	12	12

Run I Performance Statistics

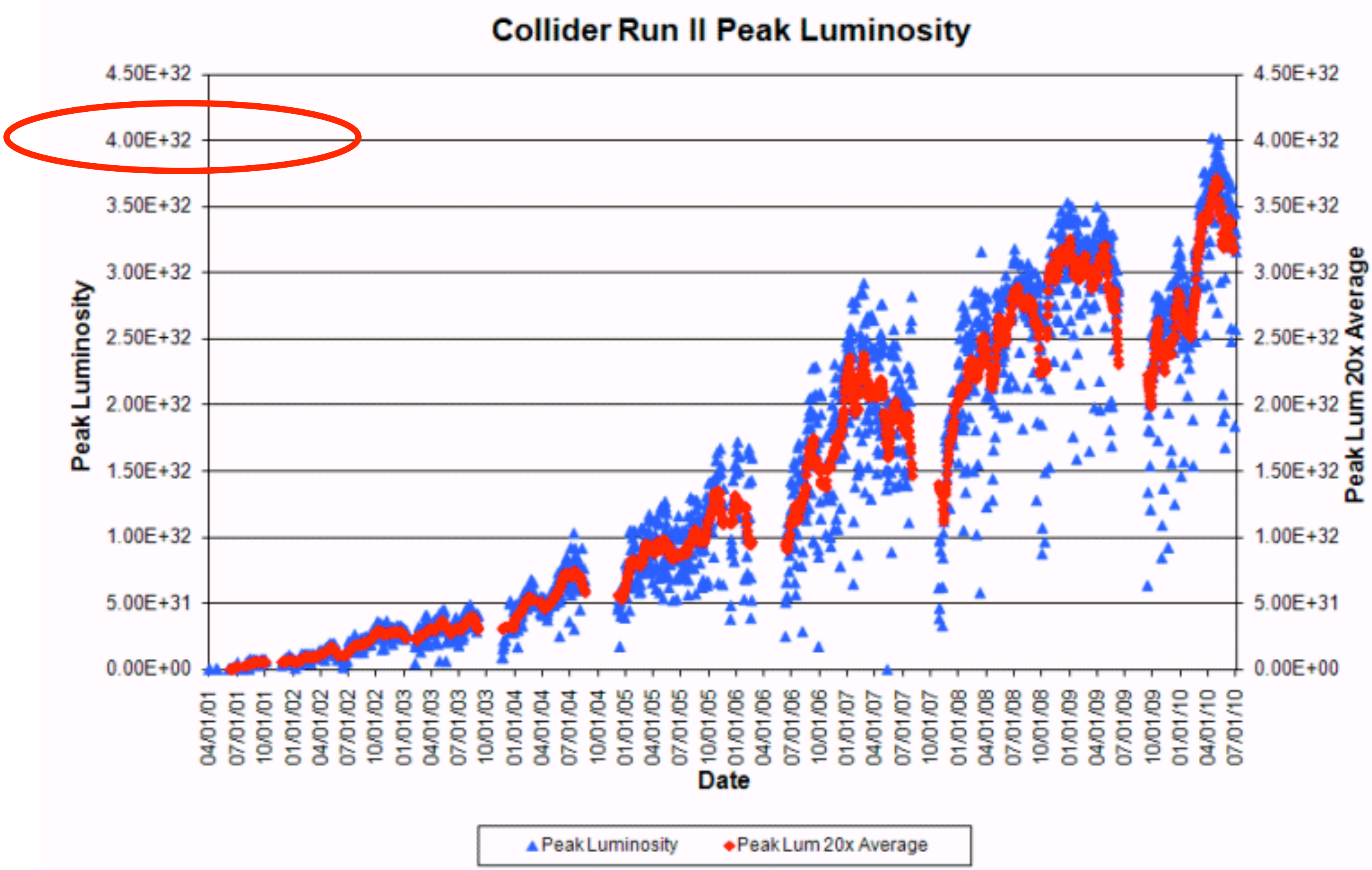
	Run Ia	Run Ib
Duration	August 1992-June 1993	November 1993-February 1996
Peak Luminosity	9.2×10^{30} cm^{-2} sec^{-1}	2.5×10^{31} cm^{-2} sec^{-1}
Typical Luminosity	5×10^{30} cm^{-2} sec^{-1}	1.6×10^{31} cm^{-2} sec^{-1}
Stacking Rate	4.85×10^{10} hr^{-1}	7.02×10^{10} hr^{-1}
Maximum Stack Size	150×10^{10} $\bar{p}$'s	221×10^{10} $\bar{p}$'s
Delivered Integrated Luminosity	31.7 pb^{-1}	147 pb^{-1}

25 times the original design luminosity
12 times larger then achieved in Run 0

Fermilab 1977

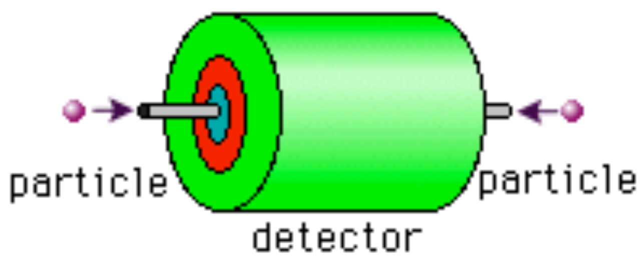
Fermilab 2002

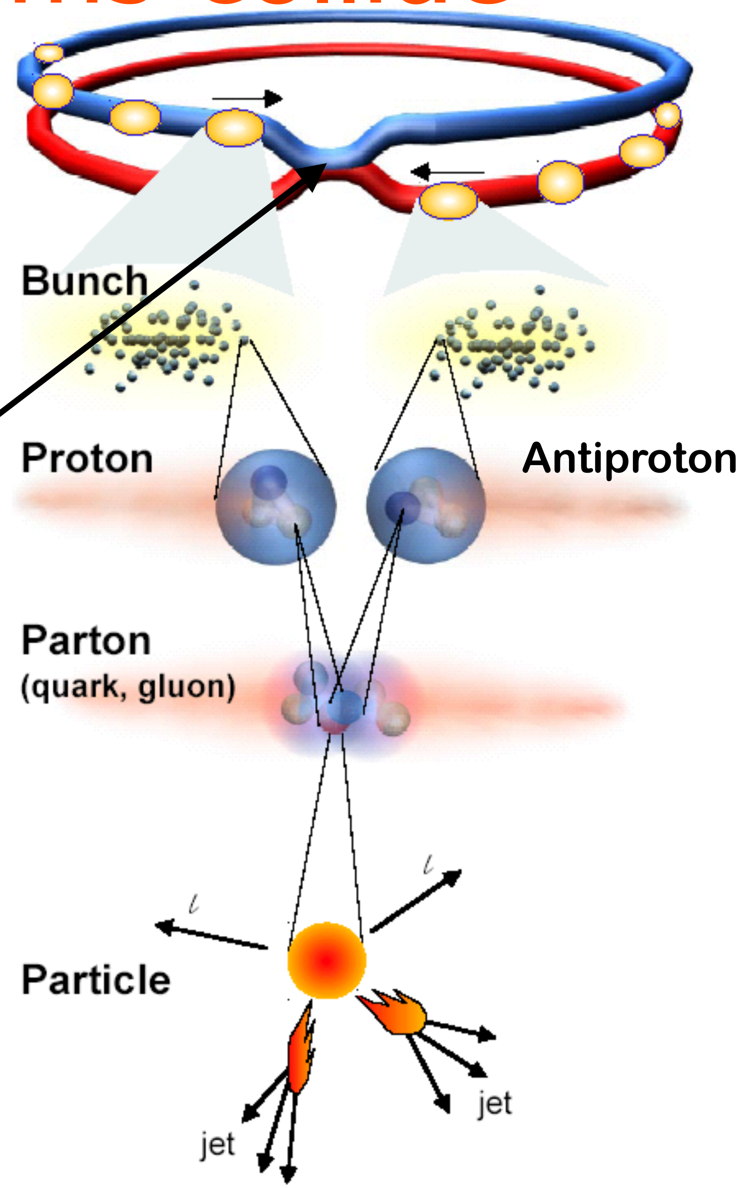
Run II Luminosity



Now let's look at what happens when beams collide

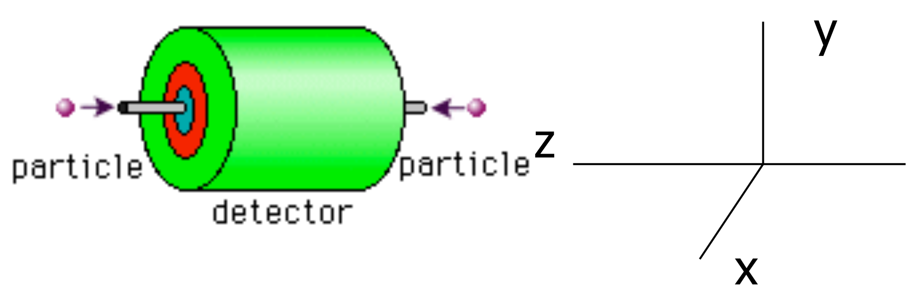
Build your detector here

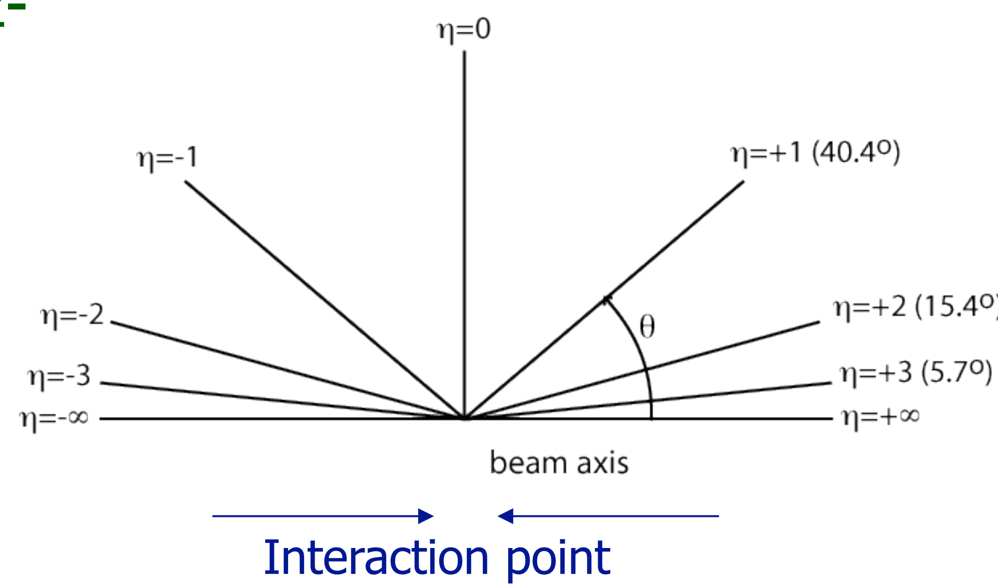




Kinematical Definitions: η

- Natural coordinates are cylindrical around the beampipe
  - θ polar angle, ϕ azimuthal angle
- Polar angle θ is not Lorentz-invariant
- **Pseudorapidity is a function of polar angle**
  - $\boxed{\eta \equiv -\log\tan(\theta/2)}$
    - $\theta = 0$ forward
    - $\theta = \pi$ backward
    - $\theta = \pi/2$ ($\eta = 0$) central





Kinematical Definitions: y

- **Rapidity** is a function of E, p_z

$$\boxed{y = \frac{1}{2}\log\frac{E + p_z}{E - p_z} = \tanh^{-1}(\frac{p_z}{E})}$$

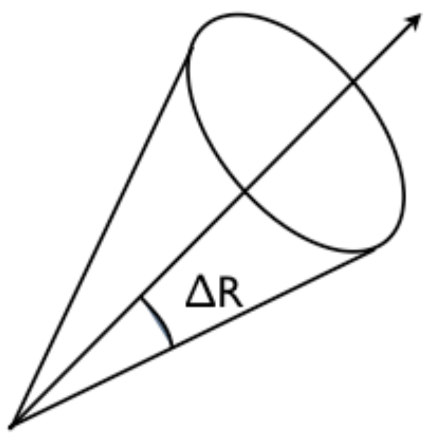
  - Δy is Lorentz-invariant under boosts along the beam direction
  - For a massless (or nearly massless particles where p>>m) particle $y=\eta$
  - Note: we can calculate η without knowing the mass of the particle!

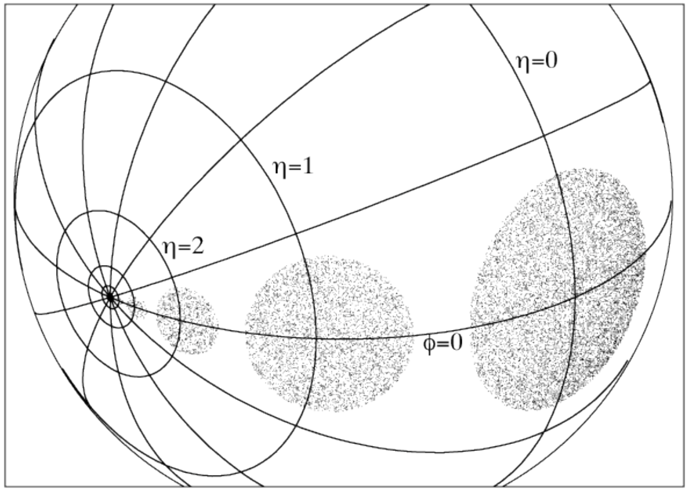
Kinematical Definitions: ΔR

- Experimentalists use ΔR as a measure of "distance":

$$\boxed{\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}}$$

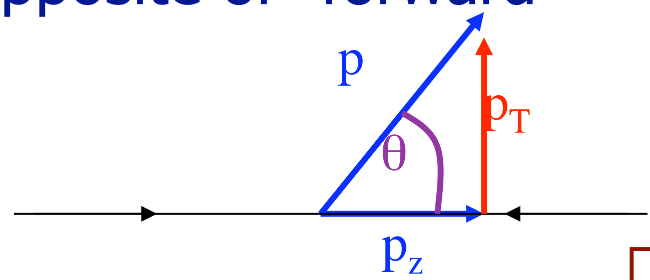
- We use it to determine separation in direction between particles
- We use "cones" of ΔR to group particles with each other in "jet" reconstruction (more on this on Wed.)





Transverse Quantities I

- At hadron colliders we focus on the transverse plane
  - opposite of "forward"



- Transverse Momentum $\boxed{p_T = p\sin\theta}$
  - Invariant under z-boosts
  - Particles that escape detection (forward) have $p_T \approx 0$
  - "Visible" transverse momentum conserved
- Transverse Energy $\boxed{E_T = E\sin\theta}$
- Transverse Mass $\boxed{m_T^2 = \sqrt{E_T^2 - p_T^2}}$
- etc…

Transverse Quantities II

- Missing transverse energy, or MET, is defined as

$$\boxed{\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ \mathrm{visible}} \vec{\mathrm{E}}_\mathrm{T}}$$

  - where nhat$_i$ is the component in the transverse plane of a unit vector that points from the interaction point to the ith calorimeter detector tower (this will become clearer later)
  - It's an event-wide z-boost-invariant quantity
  - **It's one of the most interesting and most difficult quantities for experimentalists!**
- It is also interesting to look at the measure of the scale of the visible p_T

$$\boxed{H_T \equiv \sum_{i=objects} \left|\vec{p}_{i,T}\right|}$$

  - Definition varies: which objects (leptons, jets, MET) to include in the sum
  - Also an event-wide z-boost-invariant quantity

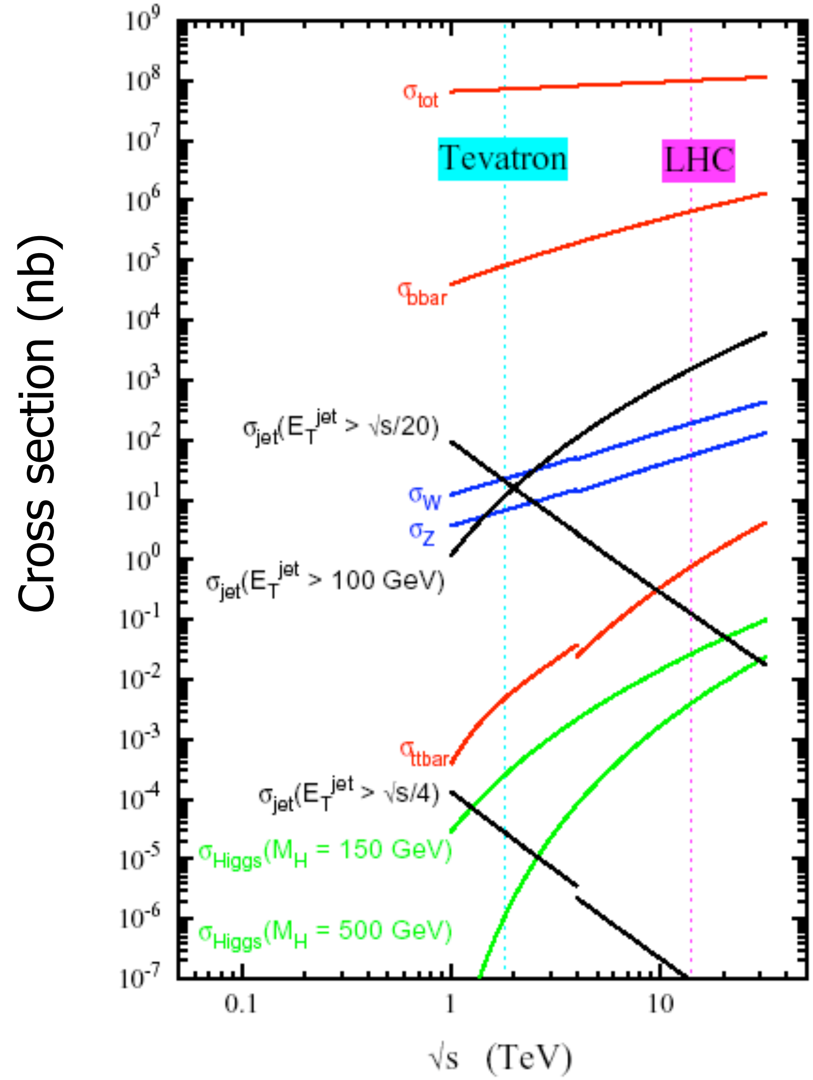
Why the transverse plane?

- why don't we look for missing p_z or missing E?
  - In hadron collisions you don't know the initial state
    - Remember, the proton is not what scatters!
  - Particles that scatter (underlying event) and escape detection have large p_z
  - Visible p_z is not conserved and is therefore not a useful variable
  - to good a approximation $\sum_i p_T^i \approx 0$
    - We have momentum conservation in transverse plane

Physics At Hadron Colliders

- QCD
- Electroweak
- flavor (charm & bottom)
- top
- Higgs
- Beyond the Standard Model?

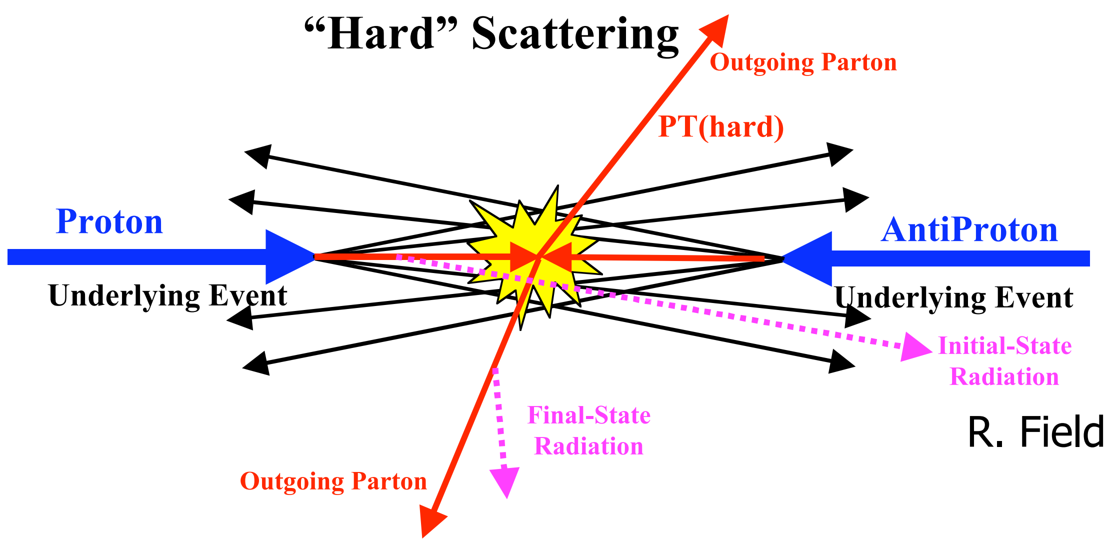
- **This is a needle-in-haystack type of science**



QCD @ Tevatron

- underlying event
- What is a jet?
- pdf's and high jet energy tails
- W/Z + jets
- top: the coming challenge for the LHC

An experimentalist's view of a hadron collision



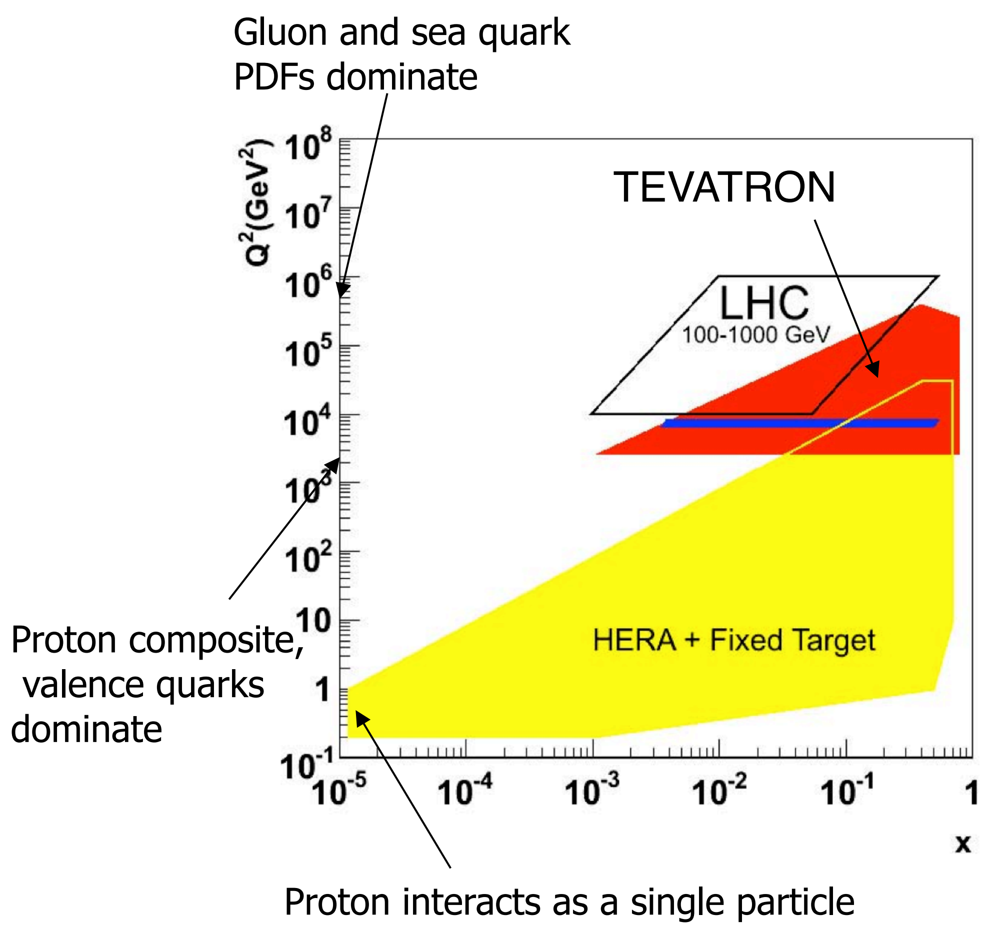
R. Field

- Proton collisions are messy!
  - Hard scattering of partons (PDFs)
  - Initial state radiation (ISR)
  - Final state radiation (FSR)
  - Underlying event (I'll define this in a moment)

- We don't know:
  - Which partons hit each other
  - What their momentum is
  - What the other partons do

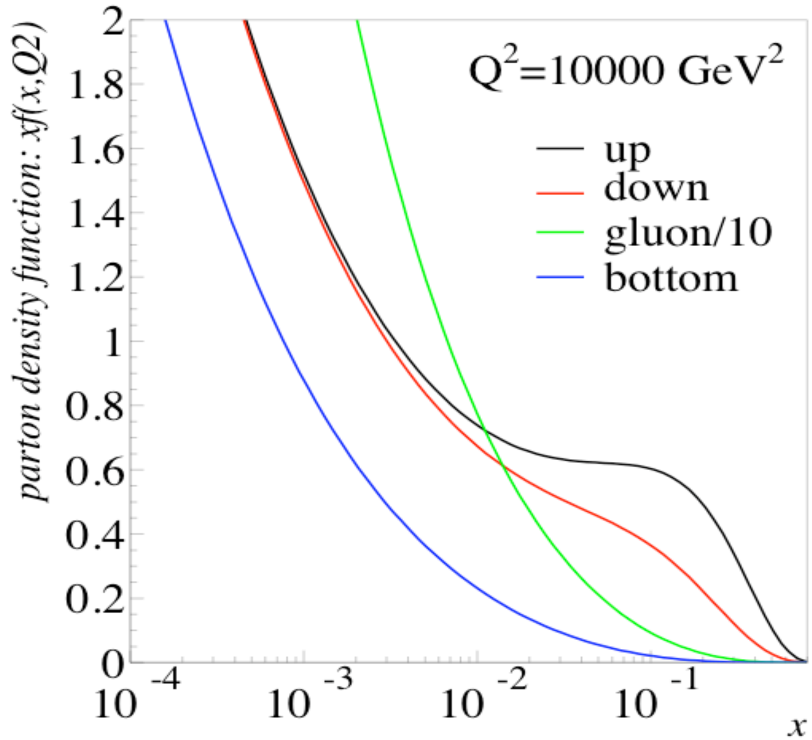
Parton Distribution Functions (I)

- PDFs describe ***quark*** and ***gluon*** content of the proton.
- PDFs are essential input to perturbative calculations at hadron colliders
  - Important for signal and background processes
  - Uncertainties can be large
- Measured in many experiments
  - mostly come from DIS data (yellow in the plot)



Parton Distribution Functions (II)

- Parton densities rise dramatically towards low x
  - gluons dominate at x < 0.1
  - u, d quarks dominate at x > 0.1
- Example:
  - Higgs: M~100 GeV
    - TeV: <x>=100/2000≈0.05
    - LHC: <x>=100/14000≈0.007
  - Results in larger cross sections at the LHC, e.g. at 14TeV
    - factor ~100 for t-tbar
    - factor ~40 for Higgs
    - factor ~10 for W's

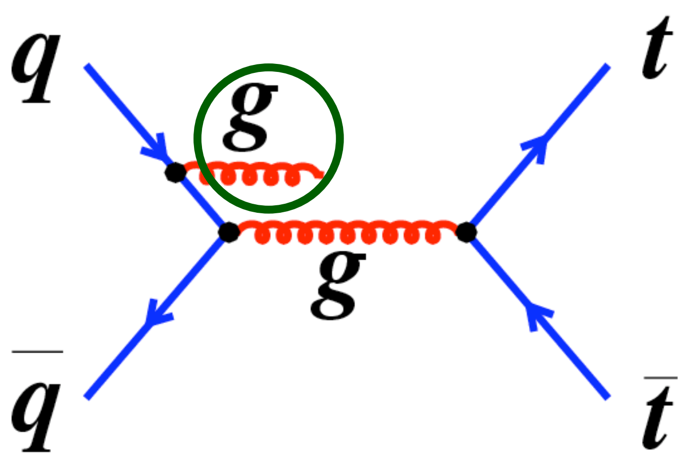


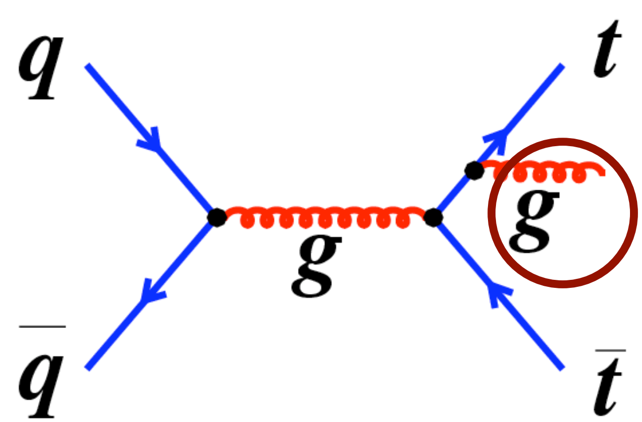
[http://durpdg.dur.ac.uk/hepdata/pdf3.html]

PDF fitting groups:
CTEQ and MRST
(now MSTW)

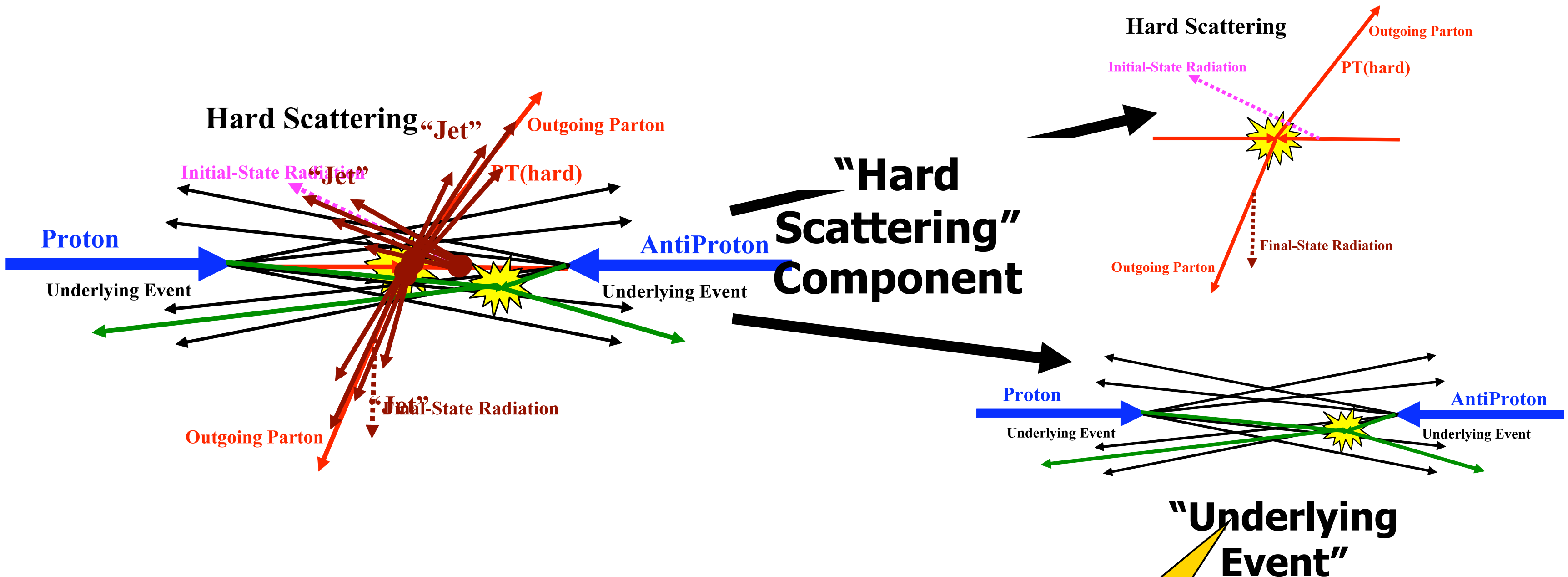
ISR/FSR

- Initial state and final state radiation can be very important even for the (apparently) simplest of processes:





MC view of a hadron collision



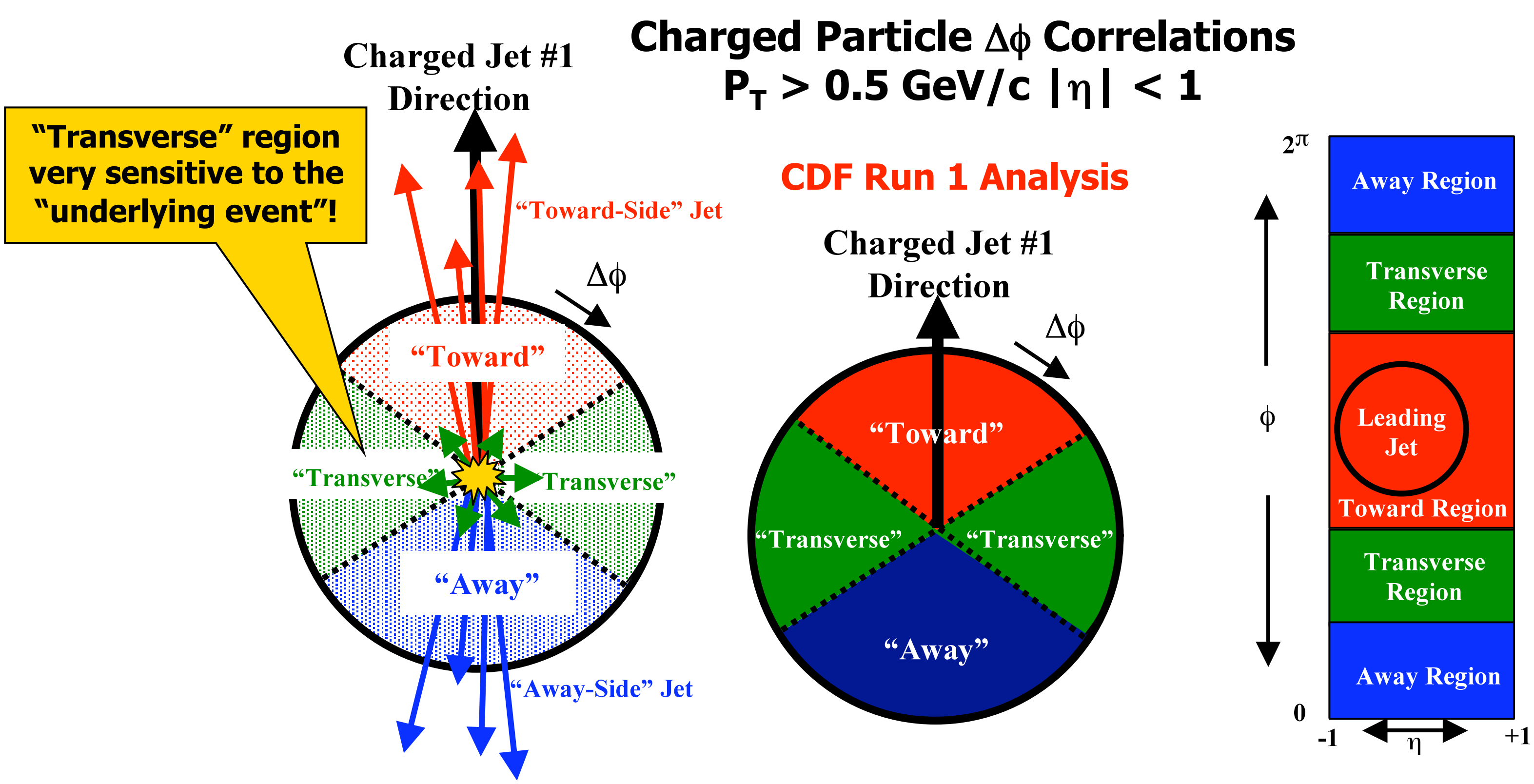
- Start with the perturbative 2-to-2 (or sometimes 2-to-3) parton-parton scat… ing and add initial and final-state gluon radiation (in the leading log approximation or modified … ding log approximation).

➡ **The "underlying event" consists of the "beam-beam remn… and from particles arising from soft or semi-soft multiple parton interactions (MP…**

➡ **Of course the outgoing colored p… and inevitably "underlying event" observables … nd final-state radiation.**

The "underlying event" is an unavoidable background to most collider observables and having good understand of it leads to more precise collider measurements!

CDF Run 1: "Underlying Event"

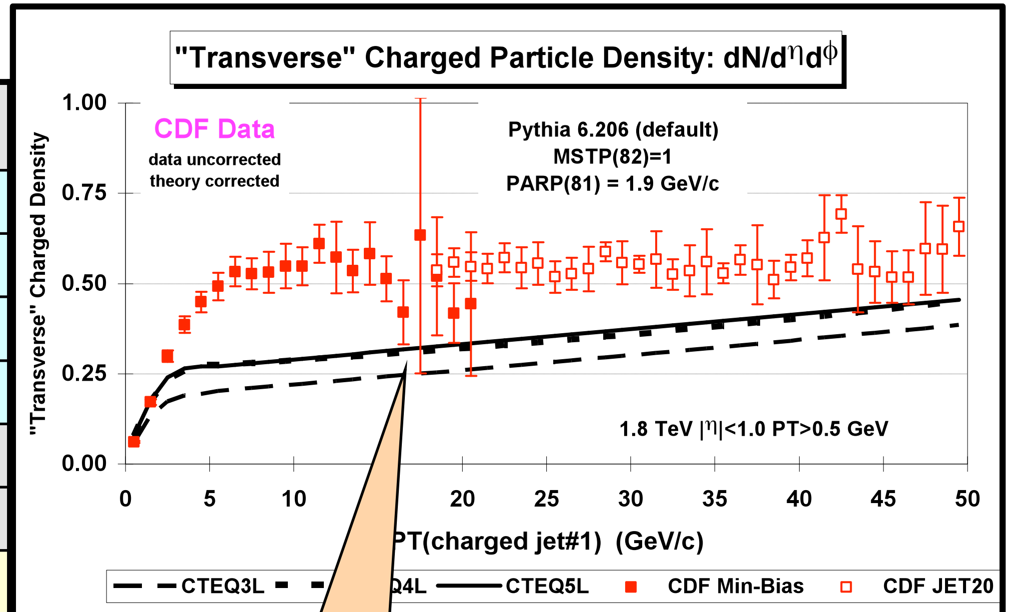


- Look at charged particle correlations in the azimuthal angle $\Delta\phi$ relative to the leading charged particle jet.
- Define $|\Delta\phi| < 60^o$ as "Toward", $60^o < |\Delta\phi| < 120^o$ as "Transverse", and $|\Delta\phi| > 120^o$ as "Away".
- All three regions have the same size in η-ϕ space, $\Delta\eta x \Delta\phi = 2x120^o = 4\pi/3$.

PYTHIA 6.206 Defaults

PYTHIA default parameters

Parameter	6.115	6.125	6.158	6.206
MSTP(81)	1	1	1	1
MSTP(82)	1	1	1	1
PARP(81)	1.4	1.9	1.9	1.9
PARP(82)	1.55	2.1	2.1	1.9
PARP(89)		1,000	1,000	1,000
PARP(90)		0.16	0.16	0.16
PARP(67)	4.0	4.0	1.0	1.0



- Plot shows the "Transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of PYTHIA 6.206 (P_T(hard) > 0) using the default parameters for multiple parton interactions and CTEQ3L, CTEQ4L, and CTEQ5L.

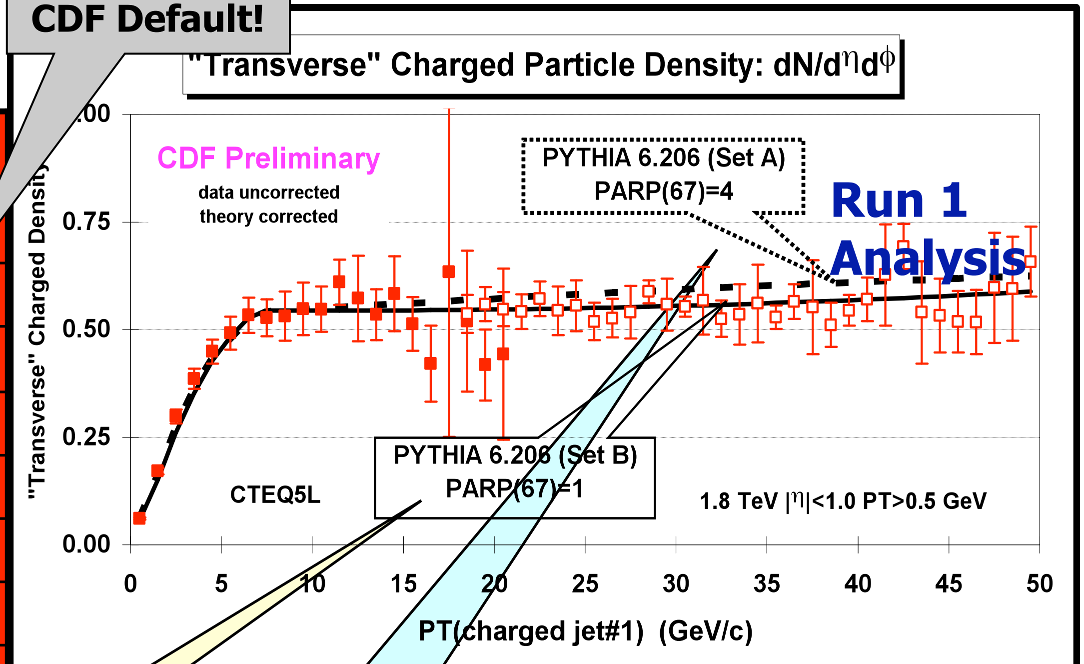
Default parameters give very poor description of the "underlying event"!

Run 1 PYTHIA Tune A

PYTHIA 6.206 CTEQ5L

Parameter	Tune B	Tune A
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	1.9 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	1.0	0.9
PARP(86)	1.0	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(67)	1.0	4.0

CDF Default!



- Plot shows the "transverse" charged particle density versus P_T(chgjet#1) compared to the QCD hard scattering predictions of two tuned versions of PYTHIA 6.206 (CTEQ5L, Set B (PARP(67)=1) and Set A (PARP(67)=4)).

New PYTHIA default (less initial-state radiation)

Old PYTHIA default (more initial-state radiation)

CDF Run 1 $P_T(Z)$

PYTHIA 6.2 CTEQ5L

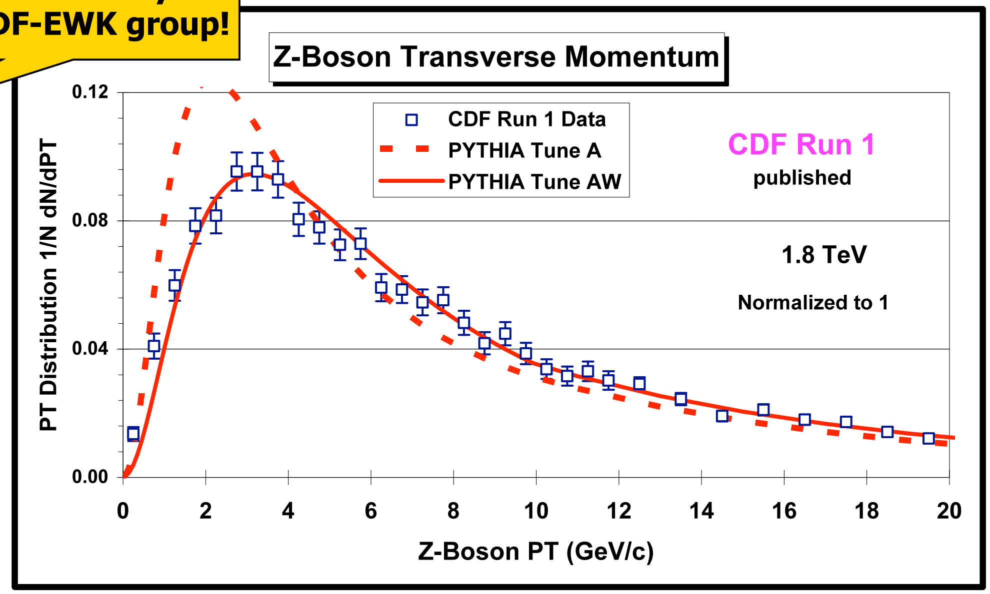
Tune used by the CDF-EWK group!

Parameter	Tune A	Tune AW
MSTP(81)	1	1
MSTP(82)	4	4
PARP(82)	2.0 GeV	2.0 GeV
PARP(83)	0.5	0.5
PARP(84)	0.4	0.4
PARP(85)	0.9	0.9
PARP(86)	0.95	0.95
PARP(89)	1.8 TeV	1.8 TeV
PARP(90)	0.25	0.25
PARP(62)	1.0	1.25
PARP(64)	1.0	0.2
PARP(67)	4.0	4.0
MSTP(91)	1	1
PARP(91)	1.0	2.1
PARP(93)	5.0	15.0

UE Parameters

ISR Parameters

Intrensic KT

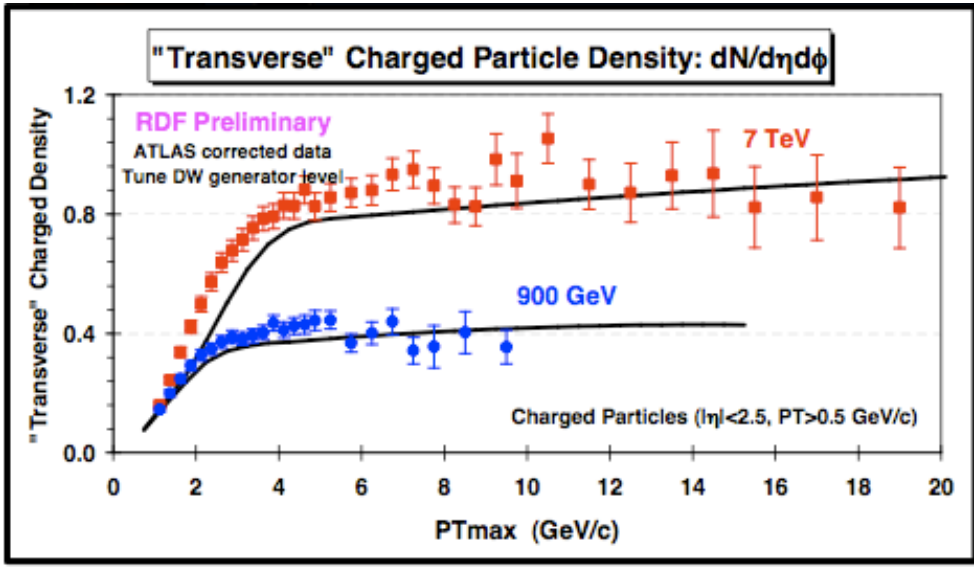


- Shows the Run 1 Z-boson p_T distribution ($\langle p_T(Z)\rangle \approx 11.5$ GeV/c) compared with PYTHIA Tune A ($\langle p_T(Z)\rangle = 9.7$ GeV/c), PYTHIA Tune AW ($\langle p_T(Z)\rangle = 11.7$

Effective Q cut-off, below which space-like showers are not evolved.

The $Q^2 = k_T^2$ in α_s for space-like showers is scaled by PARP(64)!

First LHC results!



- **ATLAS preliminary data at 900 GeV and 7 TeV on the "transverse" charged particle density, dN/dηdφ, as defined by the leading charged particle (PTmax) for charged particles with $p_T > 0.5$ GeV/c and $|\eta| < 2.5$. The data are corrected and compared with PYTHIA Tune DW at the generator level.**

Jet Definition

- From Catani, Dokshitzer, and Webber paper proposing new k_T algorithm (1992):

3. Provoking the $p\bar{p}$-collider community

Jets in $p\bar{p}$-collisions are usually defined in terms of energy measured inside cones in pseudorapidity-azimuth space [14,15]. A lot of effort has recently been devoted to setting up a standard jet definition. An agreed cone definition was achieved at the 1990 Snowmass Workshop and is known as the "Snowmass Accord" [16].

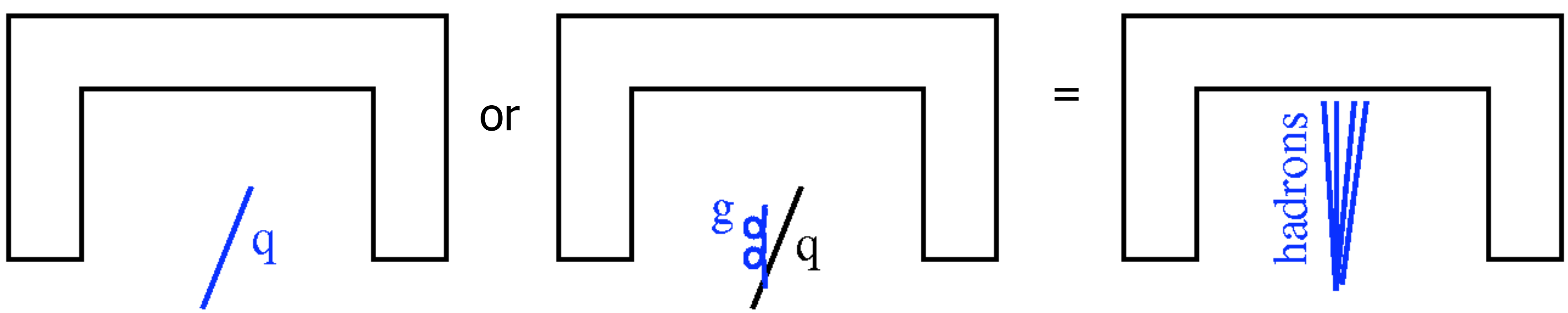
As remarked earlier, jet definitions in terms of cones suffer from some disadvantages. Firstly, it is not straightforward to generalize this type of definition to multijet events

- first published Tevatron paper using k_T: 2000…
- Lesson is learnt well by the LHC: both ATLAS and CMS reasonably quickly adopted anti-k_T

Jets: Experimentalist’s view

- What is a jet?
  - A “jet” is created when a q, qbar or gluon is kicked out of the proton
    - A hadron is created and forms a “jet” which is more or less collimated in angle, and again decays to meta-stable hadrons
      - Hadronization
  - It’s the experimentalist’s representation of a parton (more on the next slide)
- Why are they formed?
  - Remember, partons are confined!

So in reality:

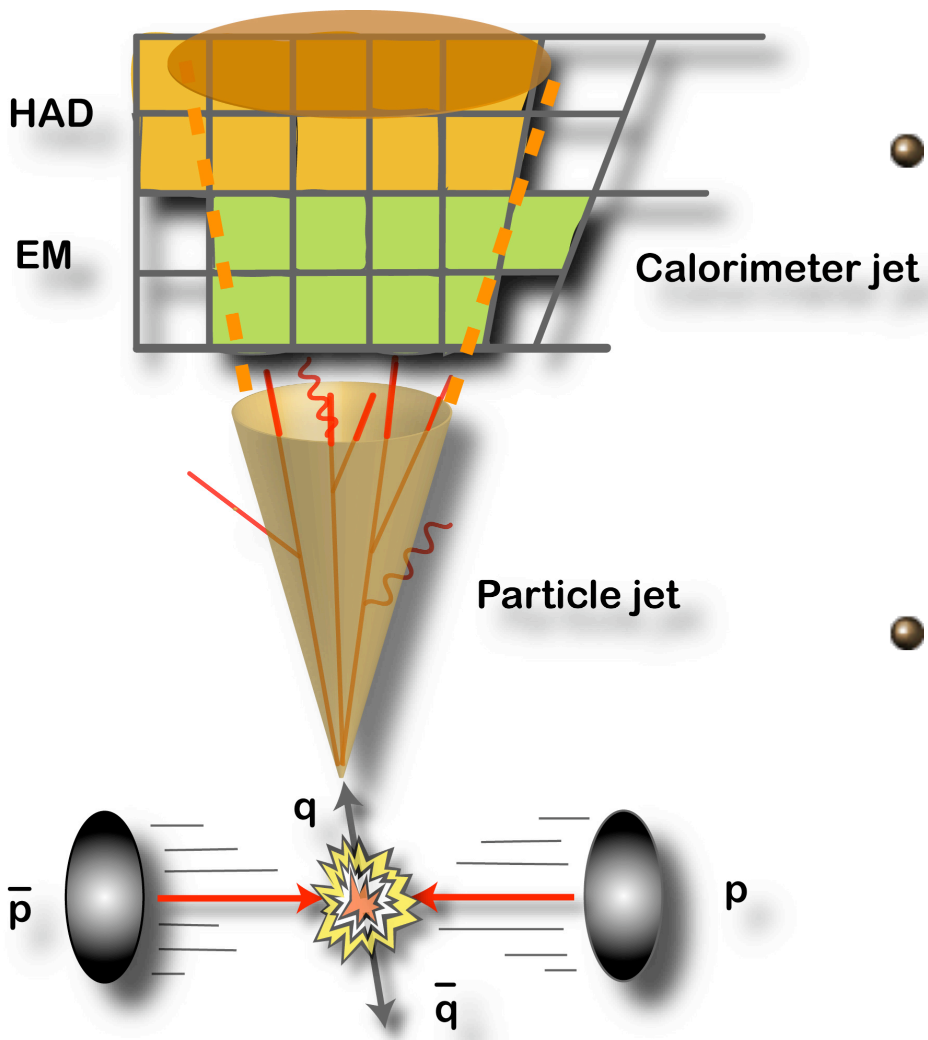


Some Experimentally Important Hadrons of QCD

	Name	Mass(MeV)	Lifetime (sec)	Dominant Decay	"Flavor"
S	π^+	140	3×10^{-8}	$\mu^+\nu_\mu$	$u\bar{d}$
	π^0	135	8×10^{-17}	$\gamma\gamma$	$u\bar{u}, d\bar{d}$
S	K^+	494	1×10^{-8}	$\mu^+\nu_\mu, \pi^+\pi^0$	$u\bar{s}$
D	K_S^0	498	9×10^{-11}	$\pi^+\pi^-, \pi^0\pi^0$	$d\bar{s}, s\bar{d}$
S	K_L^0	498	5×10^{-8}	$\pi\pi\pi, \pi\ell\nu$	$d\bar{s}, s\bar{d}$
	η	548	6×10^{-19}	$\gamma\gamma, 3\pi^0$	$u\bar{u}, d\bar{d}, s\bar{s}$
	ρ^+	770	4×10^{-24}	$\pi^+\pi^0$	$u\bar{d}$
	ρ^0	770	4×10^{-24}	$\pi^+\pi^-$	$u\bar{u}, d\bar{d}$
	ω	782	8×10^{-23}	$\pi^+\pi^-\pi^0$	$u\bar{u}, d\bar{d}$
	K^{*+}	892	1×10^{-23}	$K^+\pi^0, K^0\pi^+$	$u\bar{s}$
	K^{*0}	896	1×10^{-23}	$K^+\pi^-, K^0\pi^0$	$d\bar{s}$
	η'	958	3×10^{-21}	$\pi^+\pi^-\eta, \ldots$	$u\bar{u}, d\bar{d}, s\bar{s}$
	p	938	$> 10^{42}$	–	uud
	n	940	887	$pe^-\bar{\nu}$	udd
	ϕ^0	1020	1×10^{-22}	$K^+K^-, K_L^0K_S^0$	$s\bar{s}$
D	Λ	1115	2×10^{-10}	$p\pi^-, n\pi^0$	uds
D	Σ^+	1189	8×10^{-11}	$p\pi^0, n\pi^+$	uus
	Σ^0	1193	7×10^{-20}	$\Lambda\gamma$	uds
D	Ξ^0	1314	3×10^{-10}	$\Lambda\pi^0$	uss
D	Ξ^-	1321	2×10^{-10}	$\Lambda\pi^-$	dss
D	Ω^-	1672	8×10^{-11}	$\Lambda K^-, \Xi^0\pi^-$	sss
d	D^+	1869	1×10^{-12}	$K + \cdots$	$c\bar{d}$
d	D^0	1864	4×10^{-13}	$K + \cdots$	$c\bar{u}$
d	B^+	5279	2×10^{-12}	$D + \cdots$	$b\bar{u}$
d	B^0	5279	2×10^{-12}	$D + \cdots$	$b\bar{d}$

- Note this is by no means an exhaustive list!

Jet Reconstruction I



- How to reconstruct the jet?
  - Group together the particles from hadronization
  - Attempt to measure the energy of the parton (whatever that means - this is also not precisely defined)
- This sounds easy but in reality is very hard!

Detectors and Particle Interactions

- Understanding the detectors (and their differences) requires a basic understanding of the interaction of high energy particles and matter
- Also required for understanding how experimentalists identify particles and make physics measurements/discoveries
- Particles can interact with:
  - atoms/molecules
  - atomic electrons
  - nucleus
- Results in many effects:
  - Ionization (inelastic)
  - Elastic scattering (Coulomb)
  - Energy loss (Bremsstrahlung)
  - Pair-creation
  - etc.

Important to understand interactions of:
- Charged Particles
  - Light: Electrons
  - Heavy: All Others (π, μ, K, etc.)
- Neutral Particles
  - Photons
  - Neutrons

Radiation Length

- The radiation length (X_0) is th characteristic length that describes the energy decay of a beam of electrons:

$$X_0 = \frac{716.4 \text{ g cm}^{-2} A}{Z(Z+1)\ln(287/\sqrt{Z})}$$

- Distance over which the electron energy is reduced by a factor of 1/e due to radiation losses only
- Radiation loss is approx. independent of material when thickness expressed in terms of X_0
- Higher Z materials have shorter radiation length
  - want high-Z material for an EM calorimeter
  - want as little material as possible in front of calorimeter

material	X_0 g/cm^2
H_2	63
Al	24
Fe	13.8
Pb	6.3

- Example:
  lead: ρ = 11.4 g/cm^3 so X_0 = 5.5 mm

- The energy loss by brem is:

$$\boxed{-\frac{dE}{dx} = \frac{E}{X_0}}$$

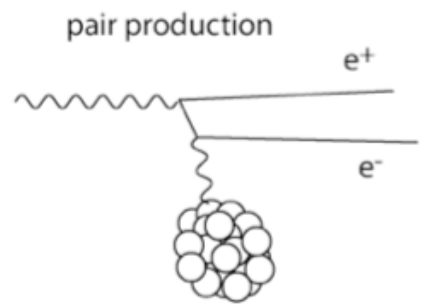
Energy Loss of Photons and EM Showers

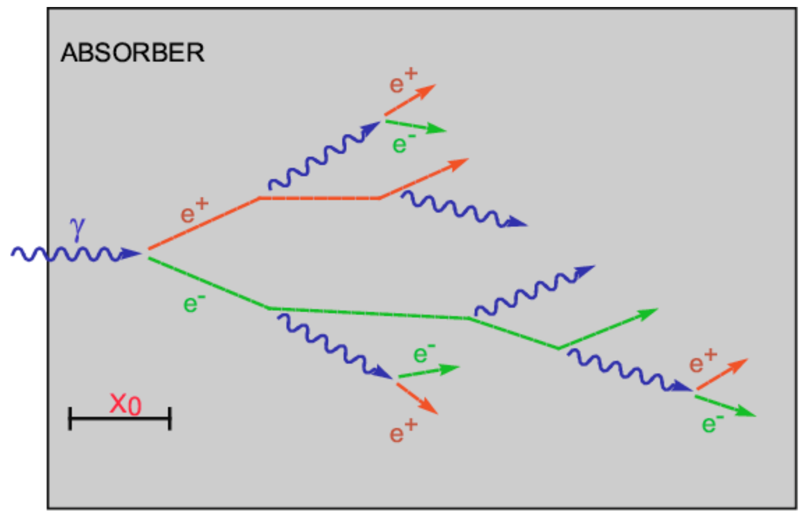
- High-energy photons predominately lose energy in matter by e+e– pair production
- The mean free path for pair production by a high-energy photon

$$\lambda = \frac{9}{7} X_0$$

- **Note for electrons $\lambda = X_0$**

- But then we have high energy electrons…so the process repeats!
  - This is an electromagnetic shower!
  - An electromagnetic cascade as pair production and bremsstrahlung generate more electrons and photons with lower energy



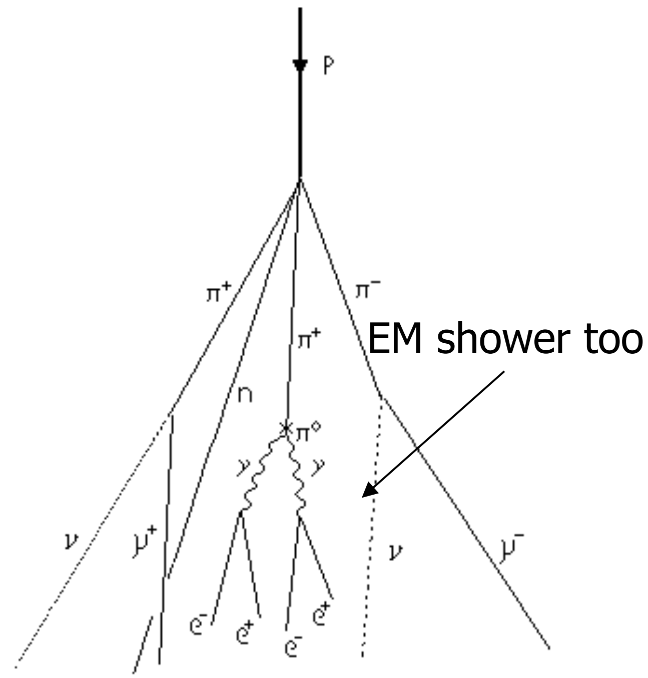


Hadronic Showers

- Interactions of heavy particles with nuclei can also produce hadronic showers
- Described by the **nuclear interaction length**

$$\lambda_n \approx 35\, g cm^{-2} A^{1/3}$$

- For heavy (high Z) materials we see that the nuclear interaction length is a lot longer than the electromagnetic one, $\lambda_n > X_0$
- So hadronic showers start later than electromagnetic showers and are more diffuse



- Example: lead ~ steel = 17 cm

material	X_0 (g/cm^2)	λ_n (g/cm^2)
H_2	63	52.4
Al	24	106
Fe	13.8	132
Pb	6.3	193

Pictures of EM and Had Showers!

Figure 2.5 A photograph of the development of an electromagnetic shower in Pb plates. The number of particles in the shower builds up geometrically. After reaching a maximum, the shower then slowly dies off due to ionization loss ([2] – with permission).

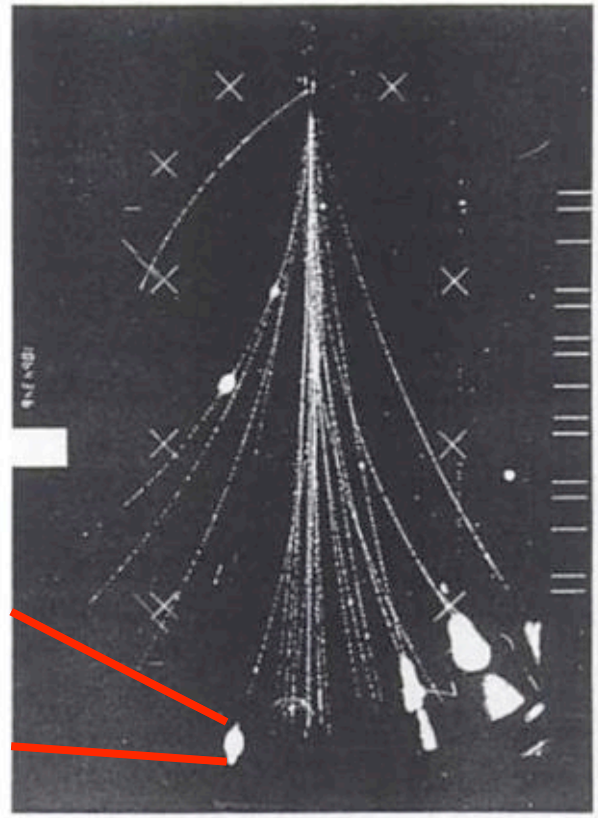
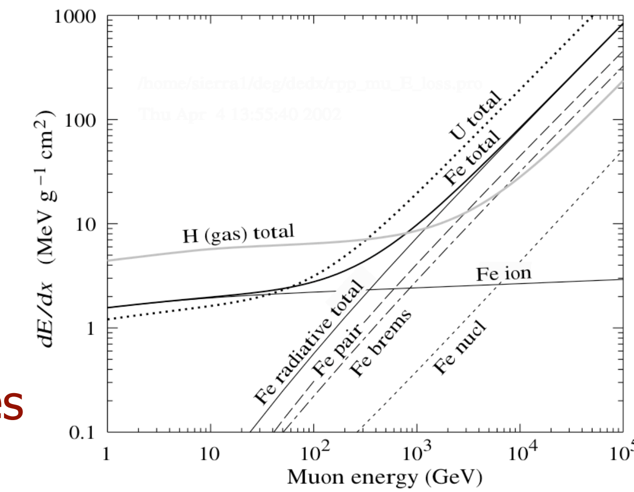


Figure 2.10 Photograph of a 200 GeV pion interaction ([5] – with permission).

Muons

- Because of it’s long lifetime, the muon for our purposes is like a stable particle
  ($c\tau \sim 700$ m)
- As we saw it is a MIP
- Also, does not feel the strong interaction
  - No hadron shower, only MIP
- Therefore, they are very penetrating
- However, at high energies muons can sometimes behave more like electrons!
  - At high energies radiative losses begin to dominate and muons can brem
  - The effective radiation length decreases at high energy and so (late) EM showers can develop in the detector

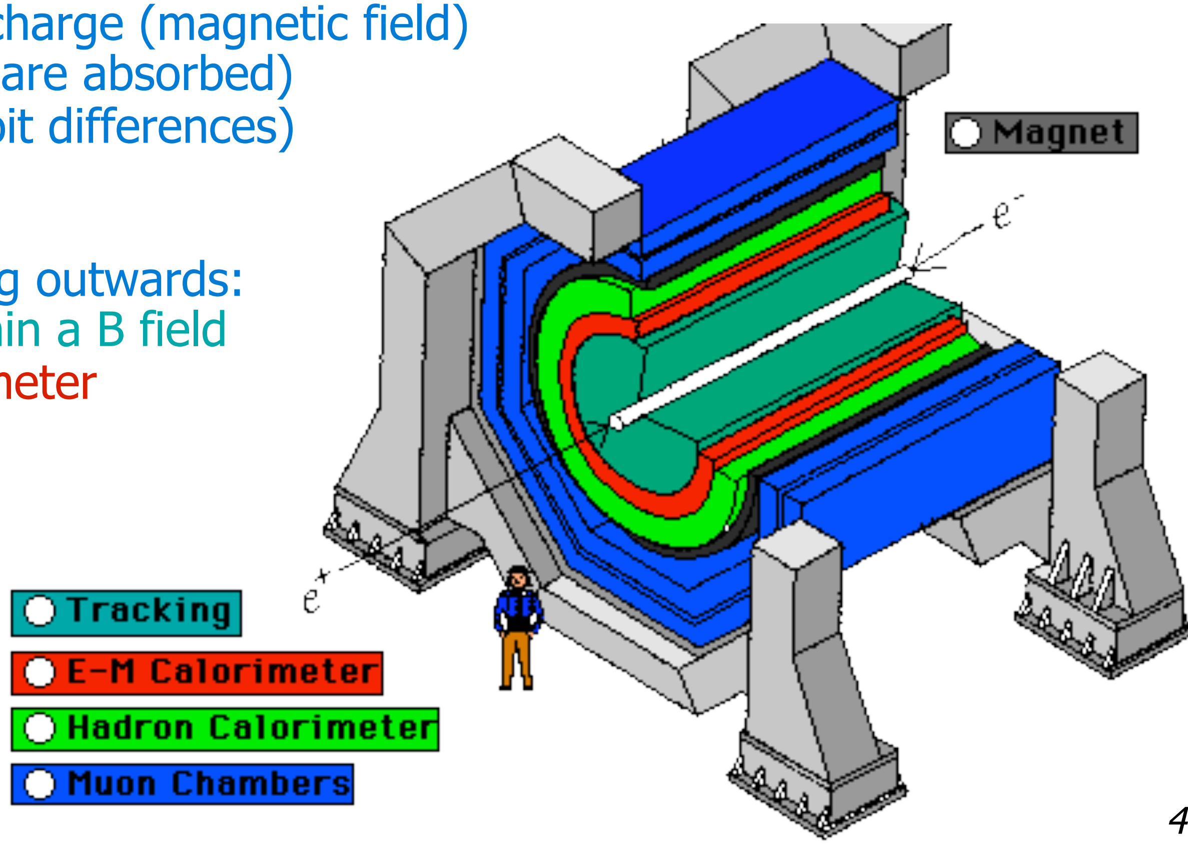


PDG

Particle Detectors

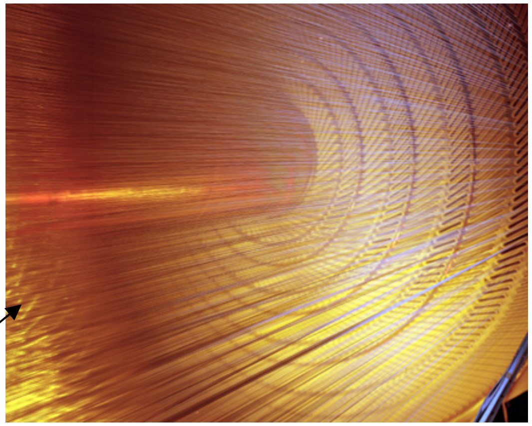
- Goal is to completely surround collision by arranging different types of detectors in layers.
- We know how particles interact with matter and we identify them (to the best of our ability!) by exploiting differences in showering, interaction with matter
- What do we want to know about the particles?
  - Their momentum and charge (magnetic field)
  - Their energy (particles are absorbed)
  - Their species (we exploit differences)

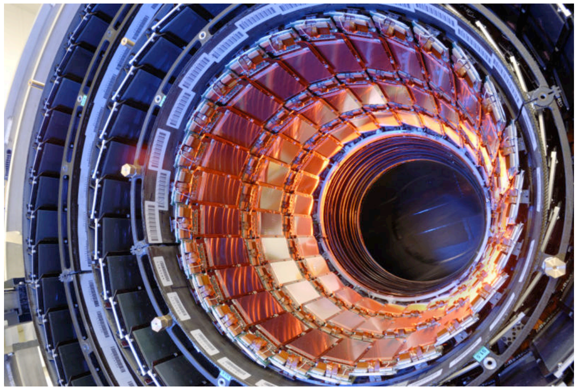
- Starting from center moving outwards:
  - Tracking detectors within a B field
  - Electromagnetic calorimeter
  - Hadronic calorimeter
  - Muon chambers



Tracking Detectors

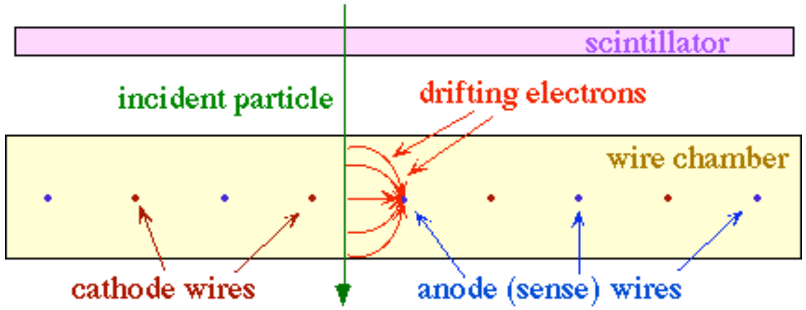
- Purpose: measure momentum and charge of charged particles
- To minimize multiple scattering, we want tracking detectors to contain as little material as possible
- Two main technologies:
  - gas/wire drift chambers (like CDF's COT)
  - solid-state detectors (silicon)
- Silicon is now the dominant sensor material in use for tracking detectors at the LHC (especially CMS)

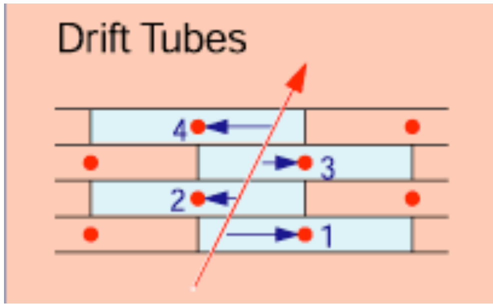




CMS

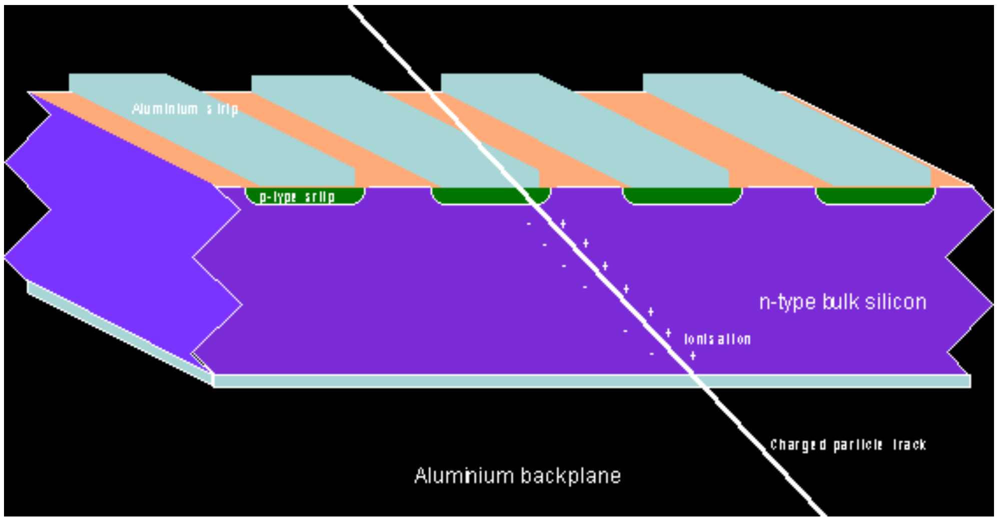
Gas/Wire Drift Chambers





- Wires in a volume filled with a gas (such as Argon/Ethan)
- Measure where a charged particle has crossed
  - charged particle ionizes the gas.
  - electrical potentials applied to the wires so electrons drift to the sense wire
  - electronics measures the charge of the signal and when it appears.
- To reconstruct the particles track several chamber planes are needed
- Example:
  - CDF COT: 30 k wires, 180 μm *hit* resolution
- Advantage:
  - low thickness (fraction of X_0)
  - traditionally preferred technology for large volume detectors

Silicon Detectors



~300μm

- Semi-conductor physics:
  - doped silicon: p-n junction
  - apply very large reverse-bias voltage to p-n junction
    - “fully depleted” the silicon, leaving E field
- Resolution 1-2% @ 100 GeV
- Important for detection secondary vertices
  - b-tagging (more on this later)

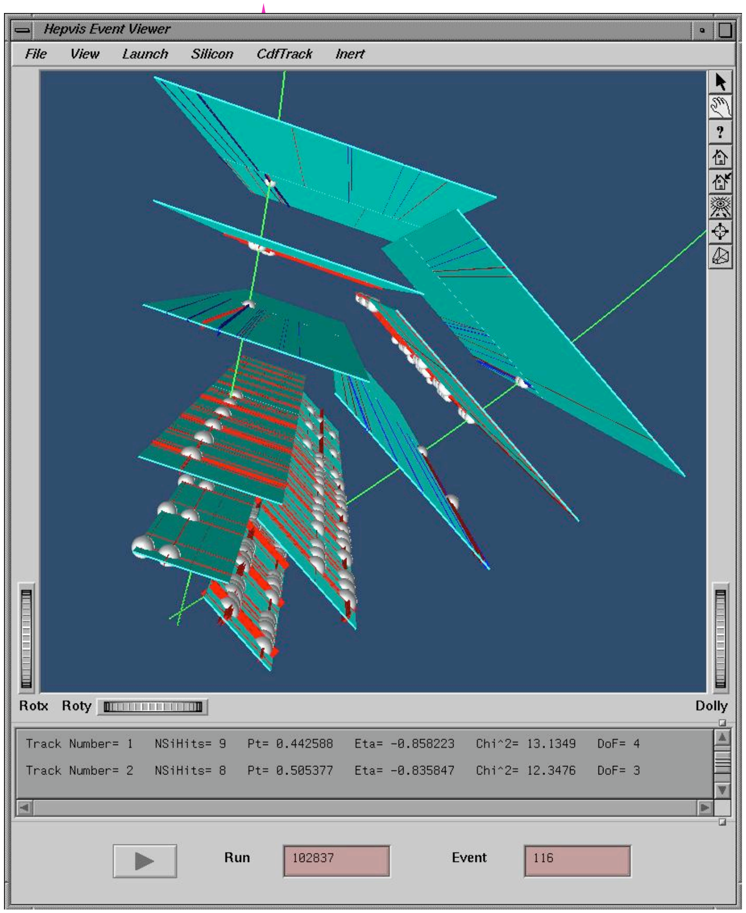
Momentum and Charge Measurement

- Since a B field is applied, by measuring a few points of the particle's track we can reconstruct the curvature of the track
  - $p_T \propto$ radius of curvature
- sagitta depends on tracking length L, p_T, and B

$$s \approx \frac{BL^2}{13.3 p_T}$$

- Example:
  - If B = 4 T, L = 1 m, p_T = 100 GeV we get a sagitta = 3 mm
- Momentum resolution $\propto p_T^2$
  - It gets worse at high p_T!

DØ

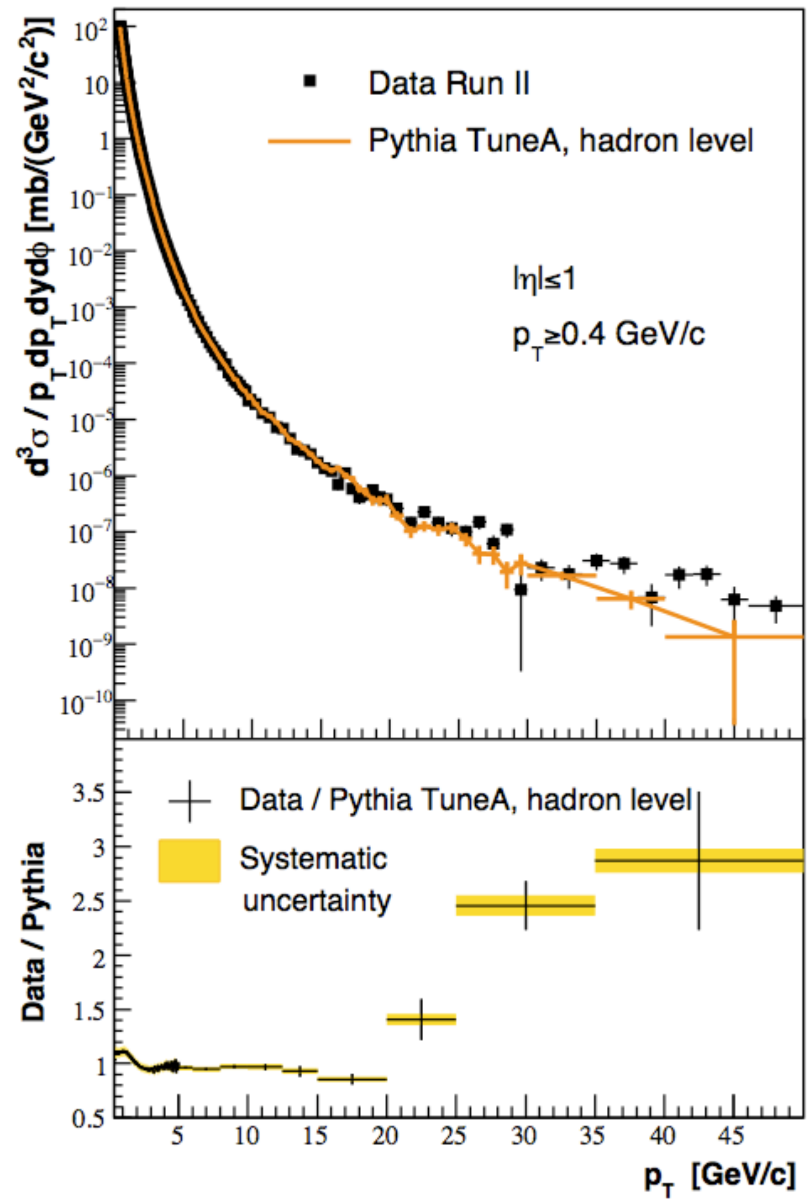


Pattern Recognition

- Picking all the right hits for a track is far from trivial
- Sometimes random hits arrange themselves in a helix
  - probability is a very high power of occupancy
- Sometimes random hit is attached to the track making distorting track parameters
- Sometimes there are interactions or decays in the tracker, and several track fragments are stitched together
- Sometimes tracks are just not helical

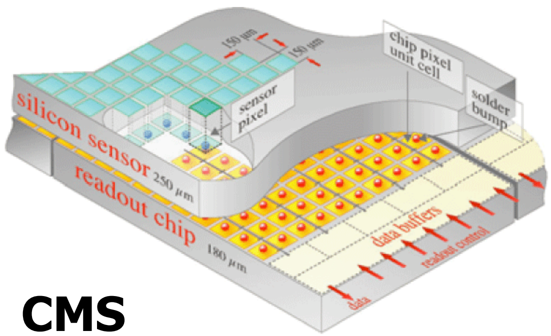
- Track quality cuts (number of tracks, χ^2) suppress such effects, but it is impossible to totally get rid of those
  - fake track pT spectrum falls much slower then the spectrum of real charged particles

But sometimes people who should know better forget about this…



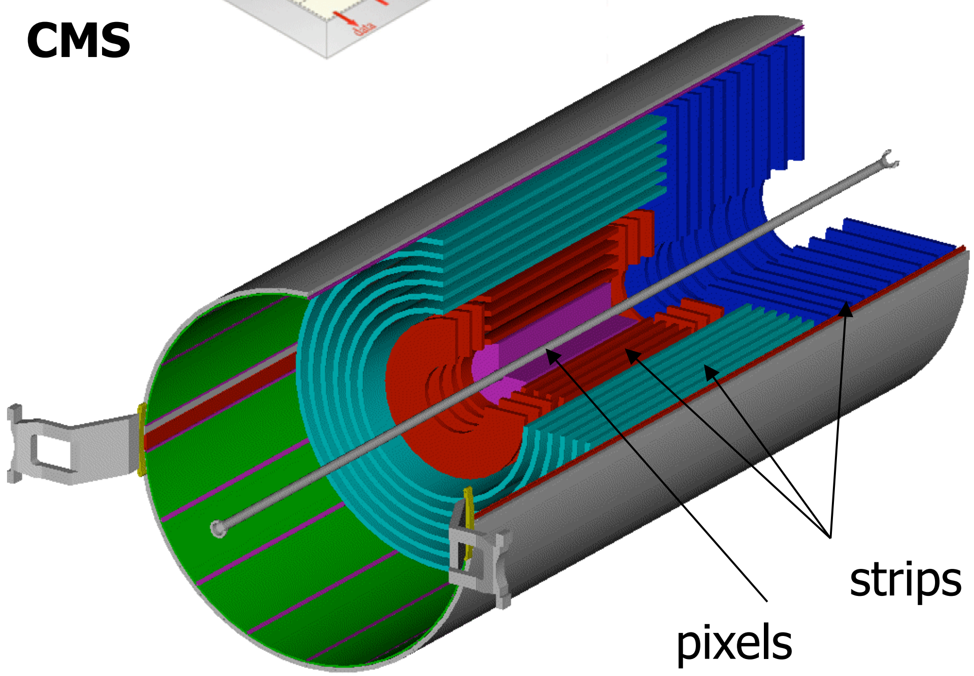
Silicon Pixel Detectors

- These detectors provide very high granularity, high precision set of measurements as close to the interaction point as possible.



	CMS	ATLAS
# Pixels	65 million	80 million

CMS



ATLAS

EM Calorimeters

- Purpose: measure energy of EM particles (charged or neutral)
- How?
  - Use heavy material to cause EM shower (brem/ pair production)
  - Total absorption / stop particles
  - Important parameter is X_0 (usually 15-30 X_0 or a high Z material)
  - There is material before the calorimeter (tracker)
- Two types of calorimeters:
  - Sampling
  - Homogeneous
- Relative energy uncertainty decreases with E !

CMS EM Cal (PbWO)

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus b \oplus \frac{c}{E}$$

Add terms in quadrature

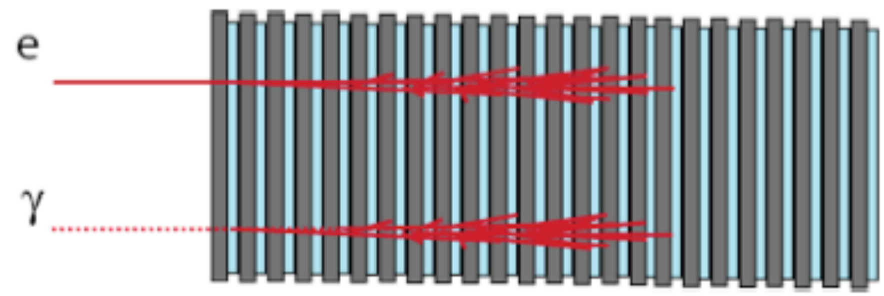
a: stochastic term (photon counting)

b: constant term

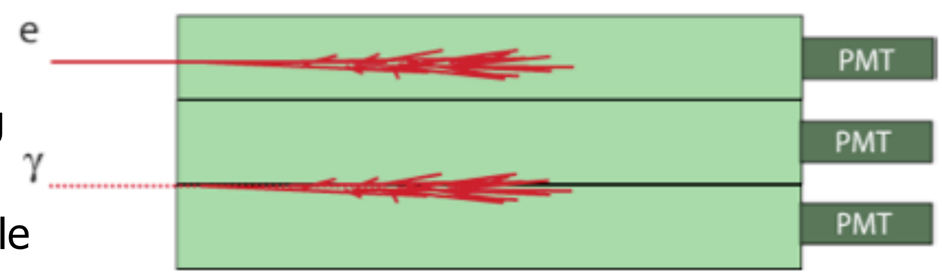
c: noise (electronics)

Sampling vs. Homogeneous Calorimeters

- Sampling calorimeter
  - active medium which generates signal
    - scintillator, an ionizing noble liquid, a Cherenkov radiator…
  - a passive medium which functions as an absorber
    - material of high density, such as lead, iron, copper, or depleted uranium.
    - σE/E ~ 10%

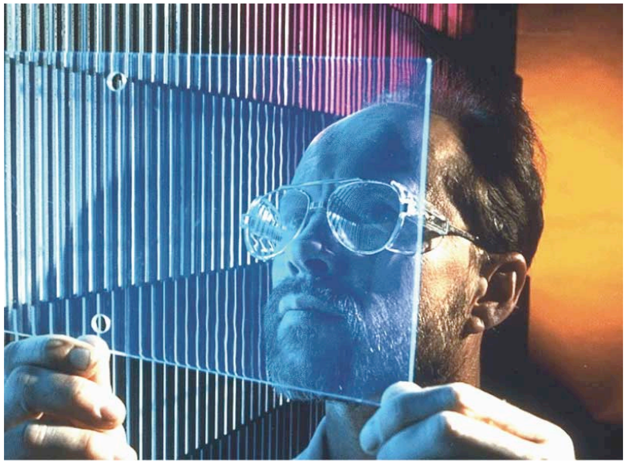


- Homogeneous calorimeter
  - the entire volume generates signal.
  - usually electromagnetic
  - inorganic heavy (high-Z) scintillating crystals
    - CsI, NaI, and PWO, ionizing noble liquids…
    - σE/E ~ 1%



Hadronic Calorimeters

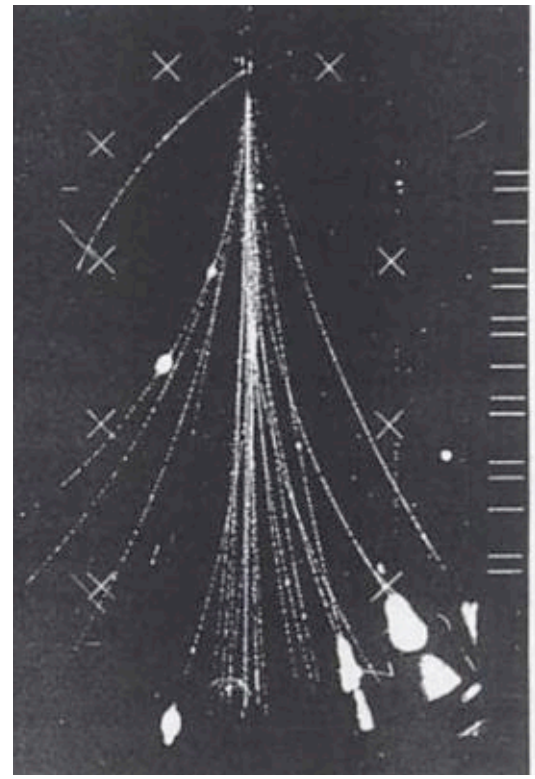
- Purpose: measure energy of hadronic/heavy particles
- How?
  - Similar to EM calorimeters but important parameter is λ_n (usually 5-8 λ_n)
  - Typically sampling calorimeters
  - Larger and coarser in sampling depth
- Resolutions typically a lot worse than EM cal.
  - Stochastic term 30-50% and higher (~80% at CDF)



Atlas Tile Cal.

Compensated Calorimetry

- Energy deposited in material by hadrons is not detected as efficiently as for electrons
- Large fluctuations in energy are due to the fluctuations of the fraction of the hadronic shower energy that went into neutral pions

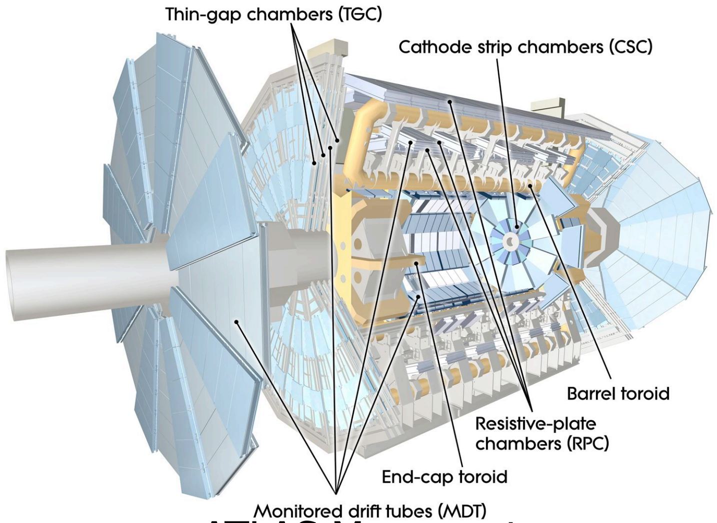


- sampling calorimeters can be made almost compensating
- crystal calorimeters are notoriously non-compensated
  - if you have crystal EM calorimeter, it almost does not matter what you use for hadronic calorimeter, since the resolution is determined by the hadronic energy fluctuations in the EM calorimeter

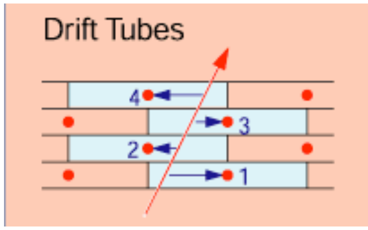
Muon Chambers

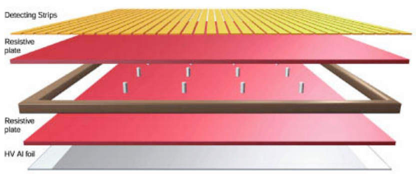
- Purpose: measure momentum / charge of muons
- Recall that the muon signature is extraordinarily penetrating
- Muon chambers are the outermost layer
- Measurements are made combined with inner tracker

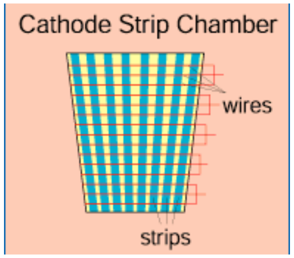
- Muon chambers in LHC experiments:
  - Series of tracking chambers for precise measurements
    - RPC's: Resistive Plate Chambers
    - DT's: Drift Tubes
    - CSC's: Cathode Strip Chambers
    - TGC's: Thin Gap Chambers



ATLAS Muon system

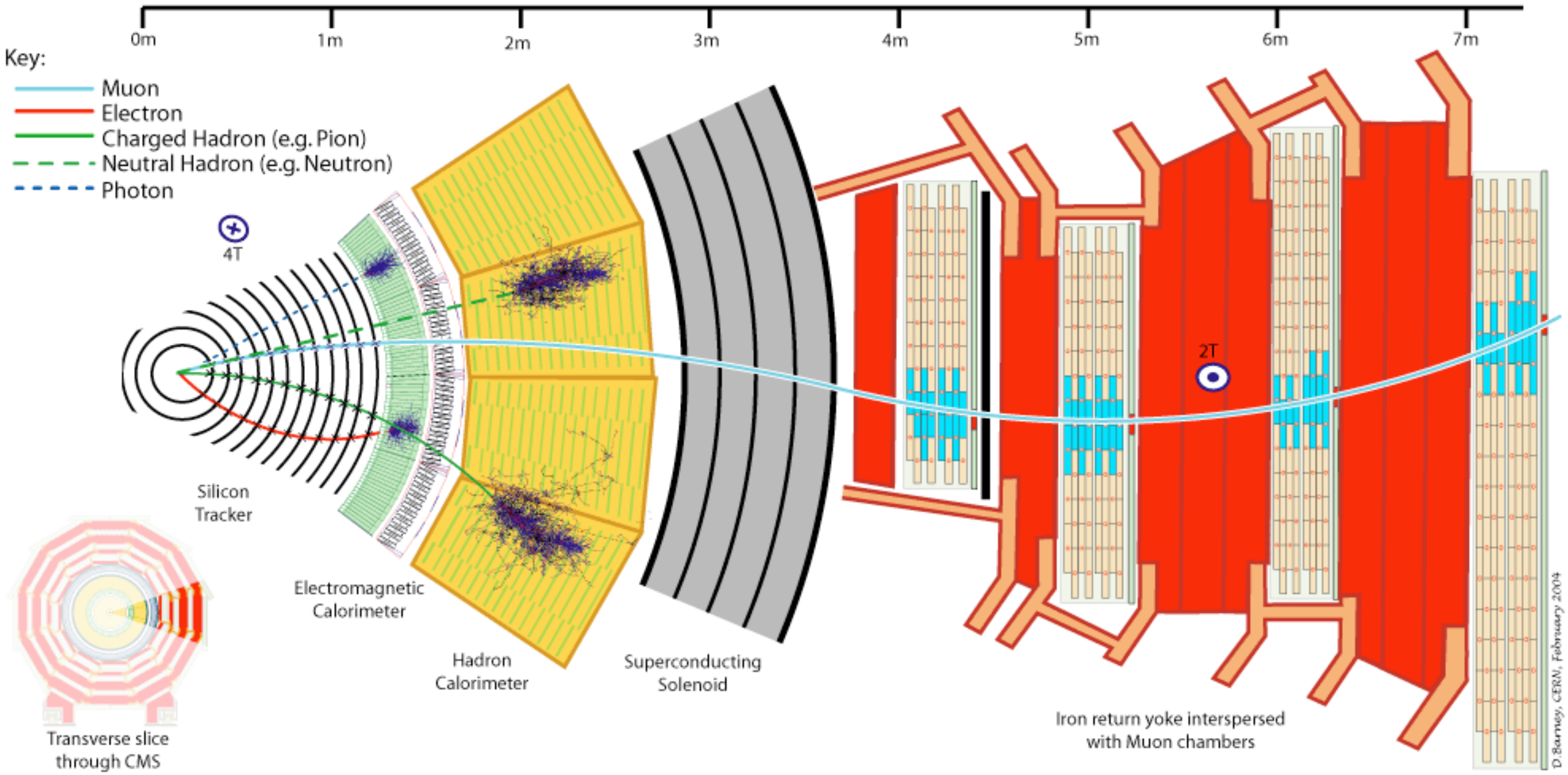






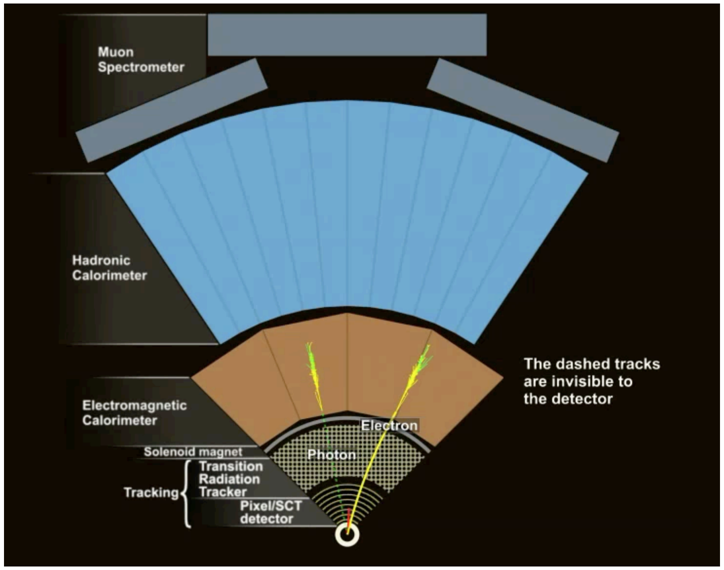

CMS Muon chambers

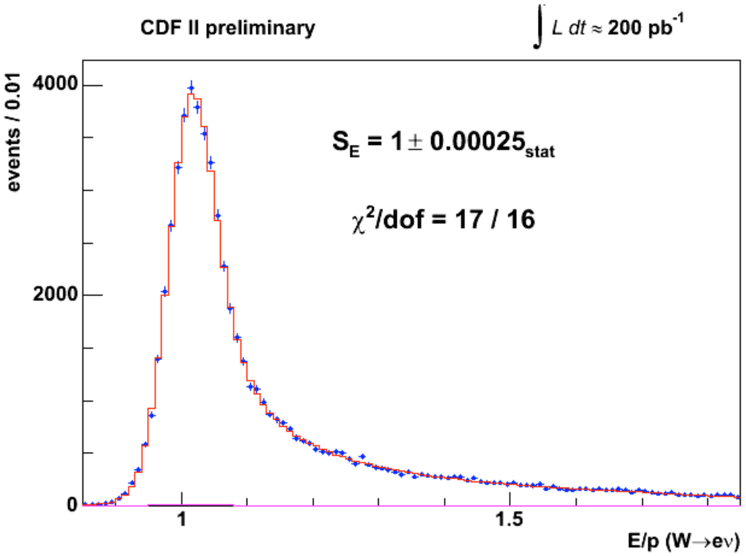
Particle Detection



Electrons and Photons

- Energy deposit in calorimeter
  - Shower shape consistent with EM shower
  - Energy loss consistent with EM particle
  - Little or no energy in had calorimeter (leakage)
- If associated with track
  - Electron
  - Additional requirements such as:
    - matching requirements on positions from track and EM cluster
    - ratio of energy (calorimeter) and momentum (track) close to unity
- If not
  - Photon





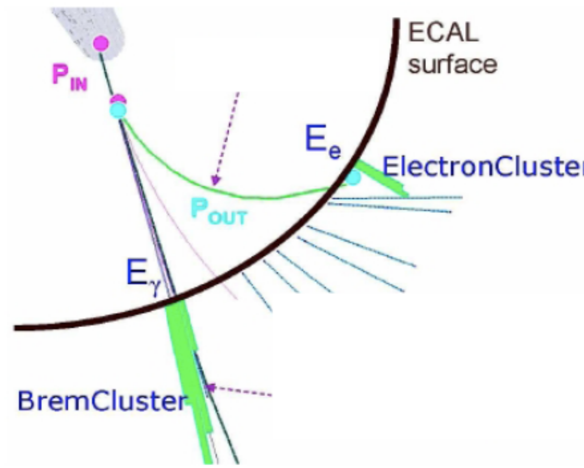
Bremstrahlung and Conversions

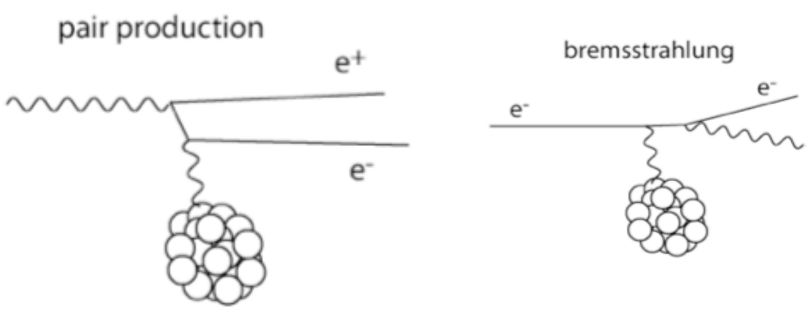
Complications:

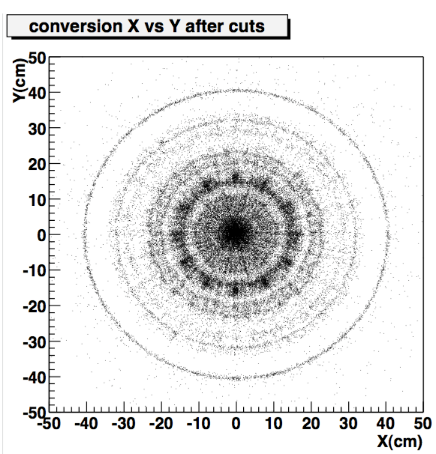
- Electrons radiate photons
- Photons pair produce electrons (conversions)

However, can be useful:

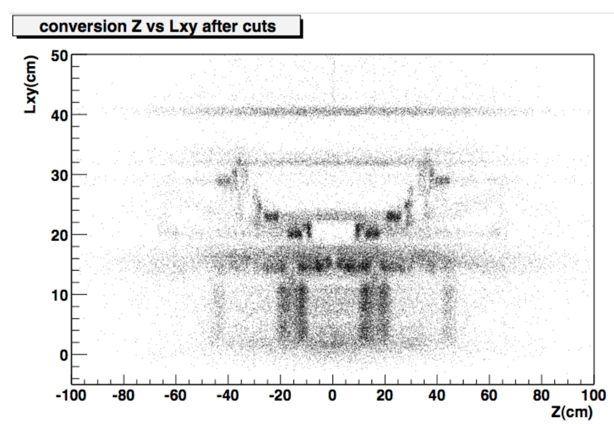
- Can use photon conversions to *x-ray* the detector and determine material before calorimeter (i.e. tracker)





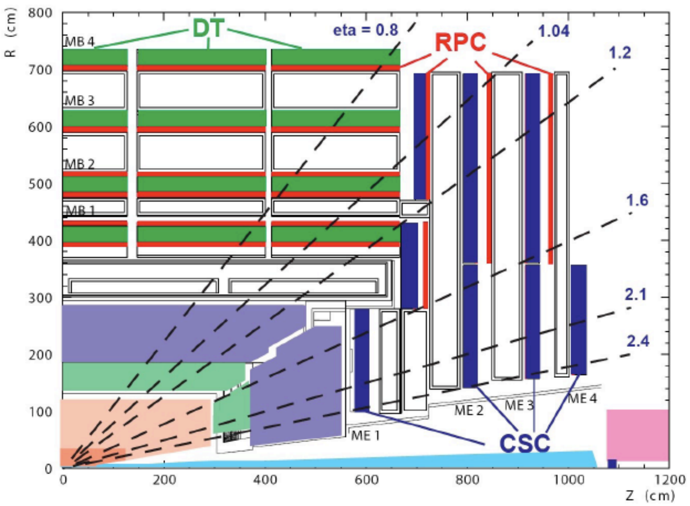


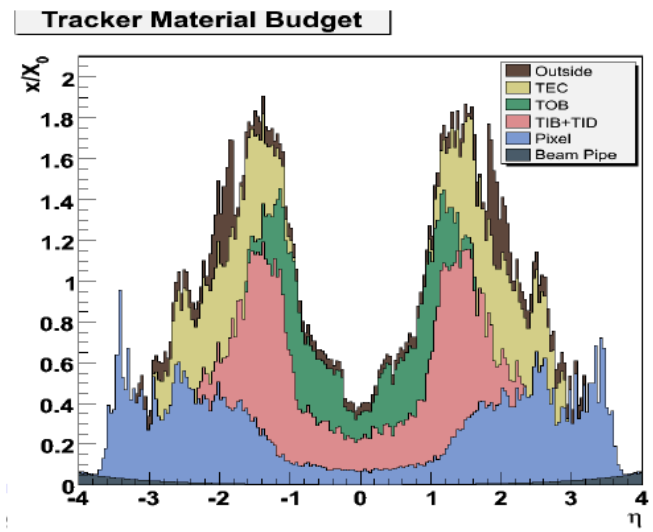
@CDF



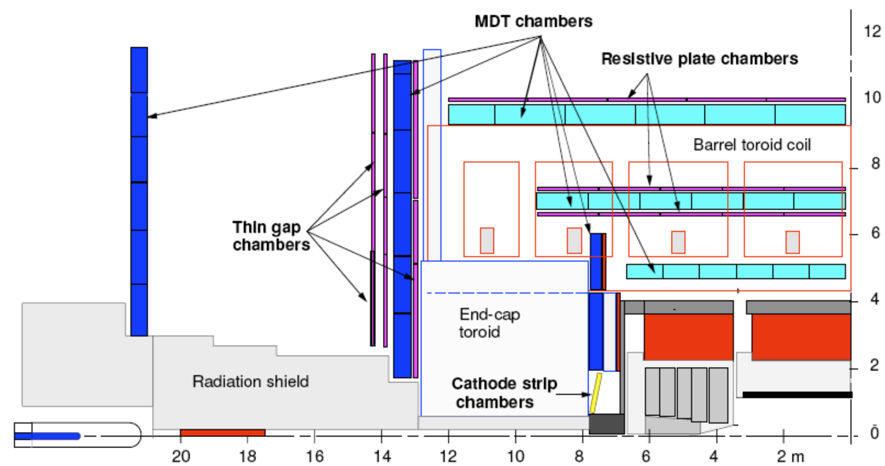
Tracker Material Budget

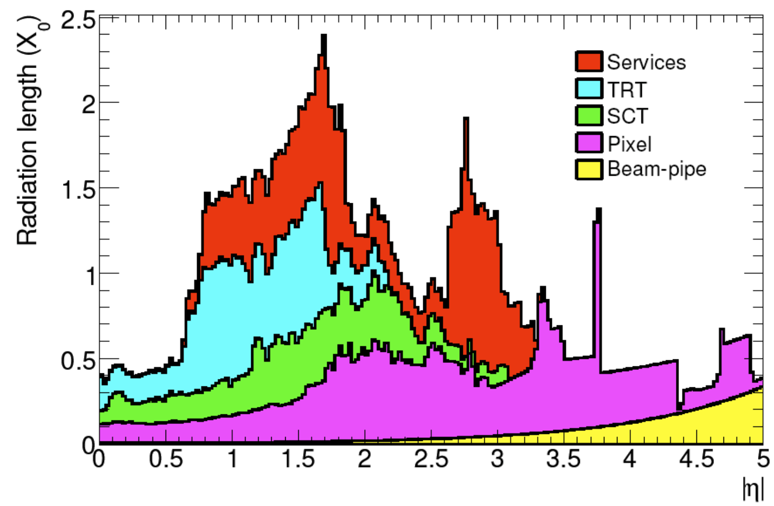
CMS





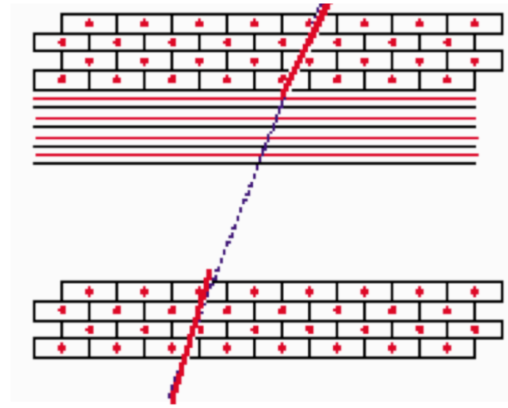
ATLAS

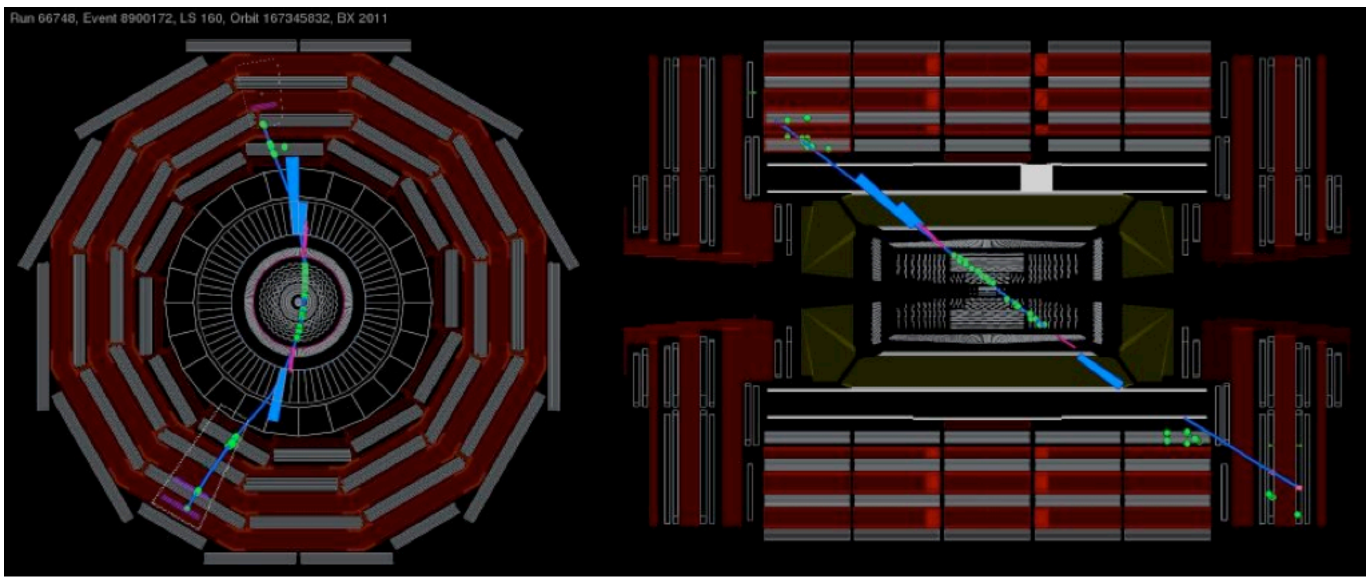




Muons

- Find tracks in the muon system
- Match with track in inner tracker
- Consistent with MIP
  - Little or no energy in calorimeters



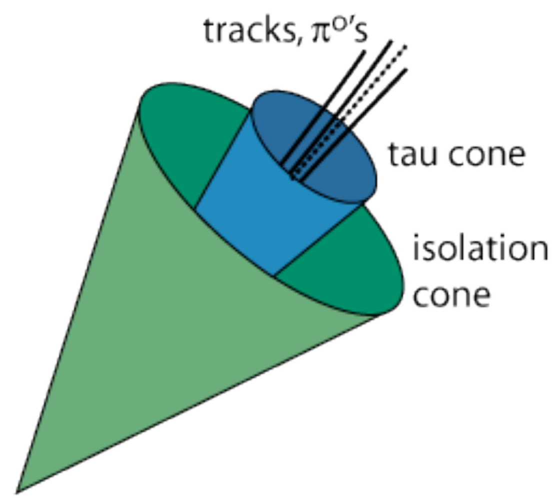


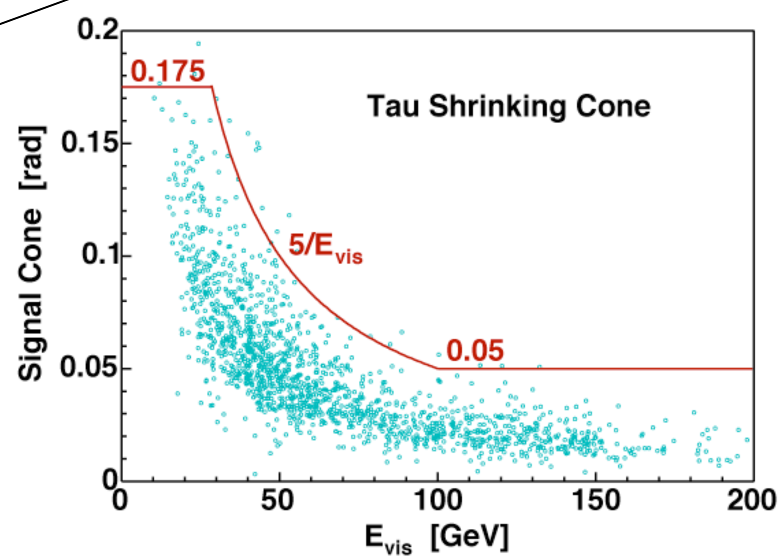
Real cosmic ray muon event in CMS detector!

Taus

- A tau lepton decays weakly
  - Always get a neutrino (i.e. MET)
- Experimentalist's jargon:
  - A "lepton" means an e or μ
  - A "tau" means a hadronically decaying tau
- Tau reconstruction
  - narrow "jets" in calorimeter
  - Form ΔR cones around tracks
    - tau cone
    - isolation cone
  - demand tracks (1 or 3) and neutral particles are within cone
- Tau ID is challenging but very sophisticated at Tevatron and LHC

$e^- \nu\nu$	17.8%
$\mu^- \nu\nu$	17.4%
$h^- \nu$	49%
$\pi^- \nu$	11%
$K^- \nu$	0.7%
$\rho^- \nu$	25.4%
$h^+ h^- h^- \nu$	15%

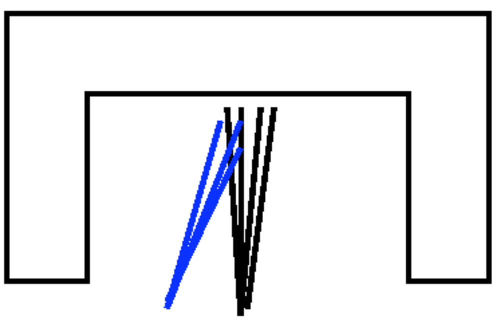




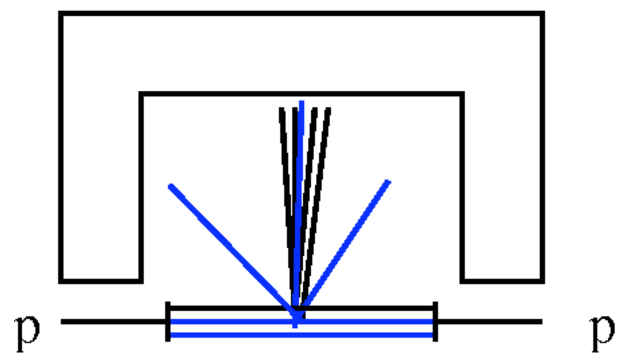
Challenges of measuring jets

- When measuring the jet energy, how can we decide which particles come from which hadronization process?
- We have lots of effects that can complicate the jet energy measurement, such as

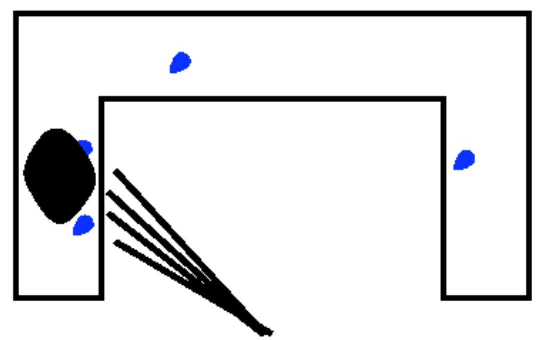
Mulitple p-p interactions:



Multiple partons in proton (spectator) interacting:



Noise in the calorimeter:



B. Heinemann

- But we have ways of correcting for such effects
  - *This calibration of the jet energy is generally called the "Jet Energy Scale" (JES)*
    - Depends on the p_T and the η of the jet (calorimeter response)

Challenes: Missing Energy

- Missing transverse energy, MET, is defined as

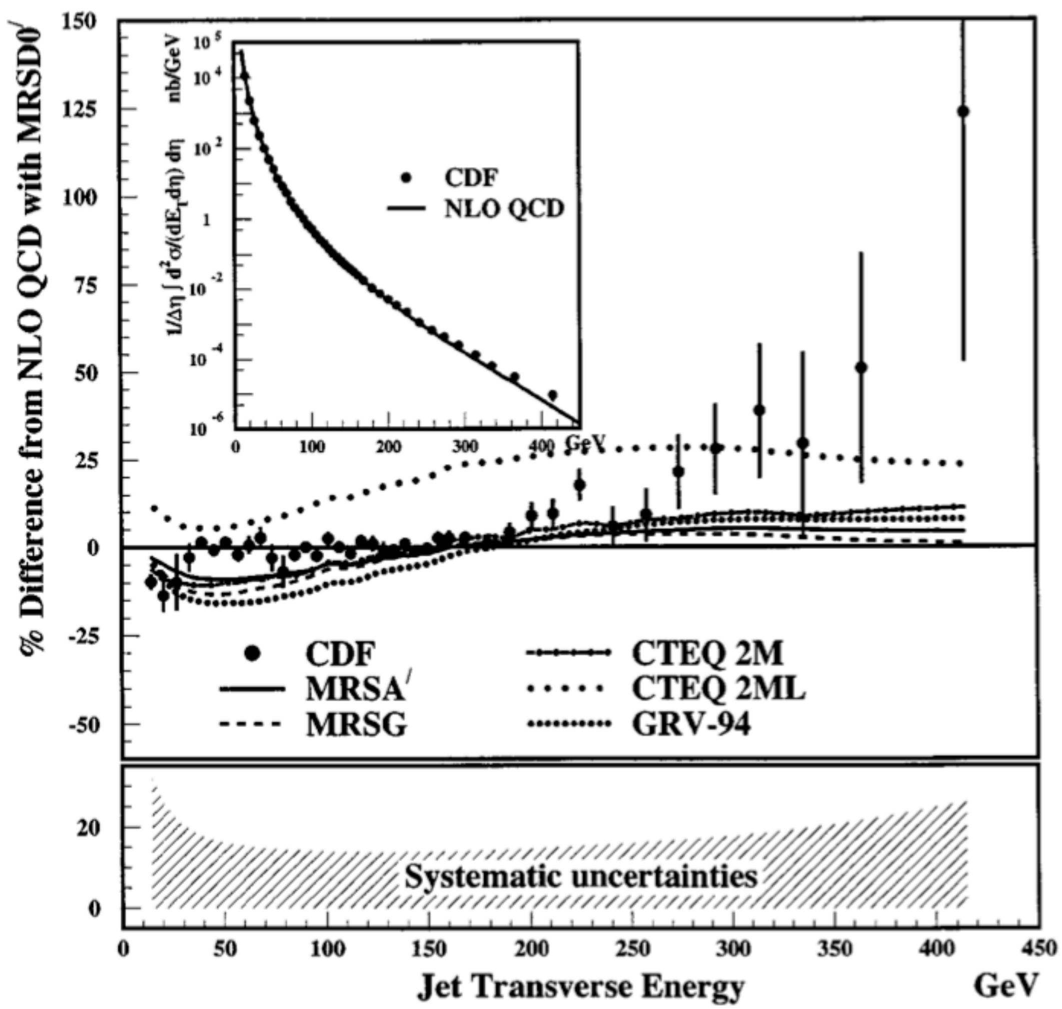
$$\not{E}_T \equiv -\sum_i E_T^i \hat{n}_i = -\sum_{all\ \mathrm{visible}} \vec{\mathrm{E}}_\mathrm{T}$$

  - where nhat$_i$ is the component in the transverse plane of a unit vector that points from the interaction point to the ith calorimeter detector tower.
  - This includes all clustered and unclustered energy
- It's one of the most interesting and most difficult quantities for experimentalists
  - **Whenever anything goes wrong you have MET!** Examples:
    - dead calorimeter cells
    - jet whose hardest hadron enters a crack in the calorimeter
    - "beam halo"
    - a very rare (but not rare enough) high-pT , high-η jet (QCD jet cross sections dominate hadron collisions)
    - forward calorimeter (not working or not calibrated)
- Therefore, we need to carefully understand this quantity
  - Very important for new physics searches

Tracks in Calorimetry and Particle Flow

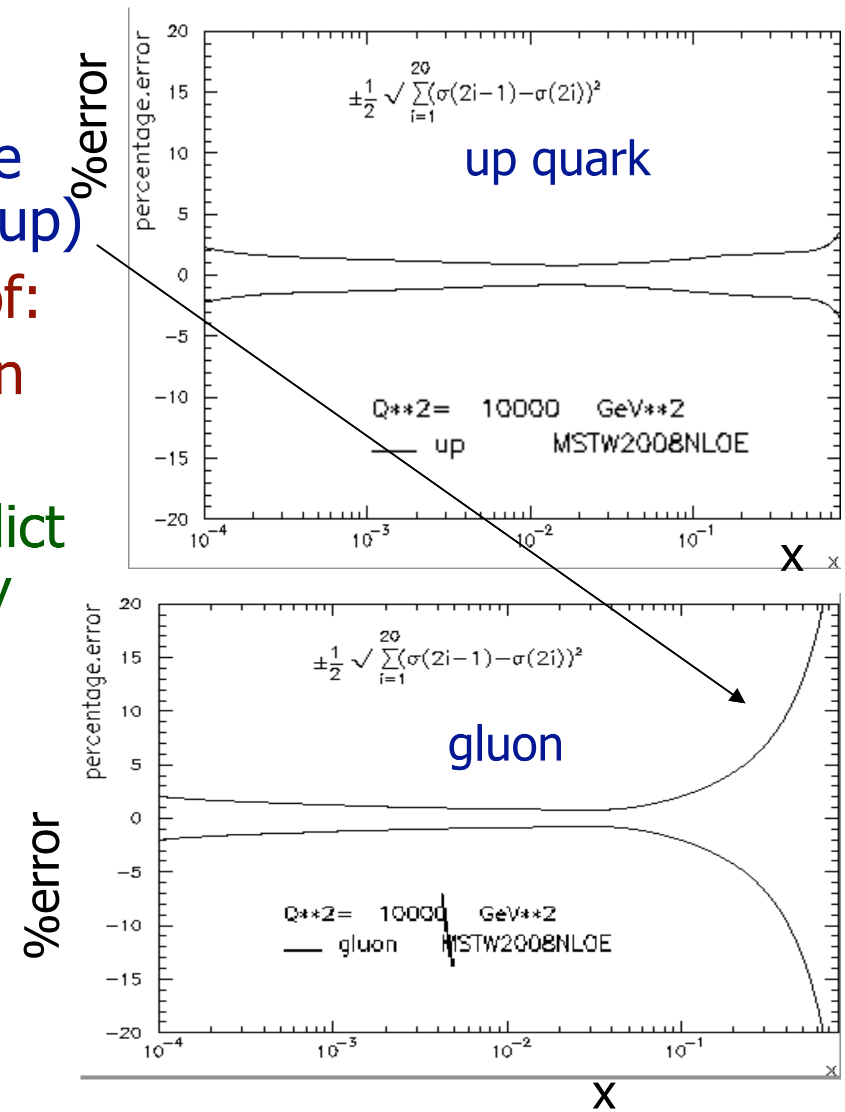
- Calorimetry is a good way to measure MET if the calorimetry is hermetic, compensated and there is no magnetic field
- Gaps in instrumentation leads to mis-measured energy
- Magnetic field curl low-momentum particles
  - totally miss them or misreconstruct direction
- Non-compensated calorimetry makes the response depend on the fraction of energy in charged pions
- Tracks plus calorimetry and particle flow are supposed to alleviate this problem
  - Worked at ee colliders, but not at the Tevatron
  - BUT, seems to be working at CMS
- Track plus calorimeter:
  - account for curled tracks
  - for hadrons reaching the calorimeter, use MC to derive <u>average</u> correction
- Particle Flow
  - attempt to make corrections for charged and neutral hadrons (n, K^0_L) on particle by particle basis
  - much higher risk of mis-reconstruction compared to tracks+cal

Ready to make jet cross section measurement?



PDF Uncertainties

- PDF uncertainties of 2-30% or more (e.g. gluon PDF uncertainties blow up)
- This quantifies our understanding of:
  - The parton content of the proton
  - The cross sections of processes
- Uncertainties mean we cannot predict well-understood processes perfectly
- Extrapolation to LHC cross section calculations can vary a lot



[http://durpdg.dur.ac.uk/hepdata/pdf3.html]

Parton Distribution Functions

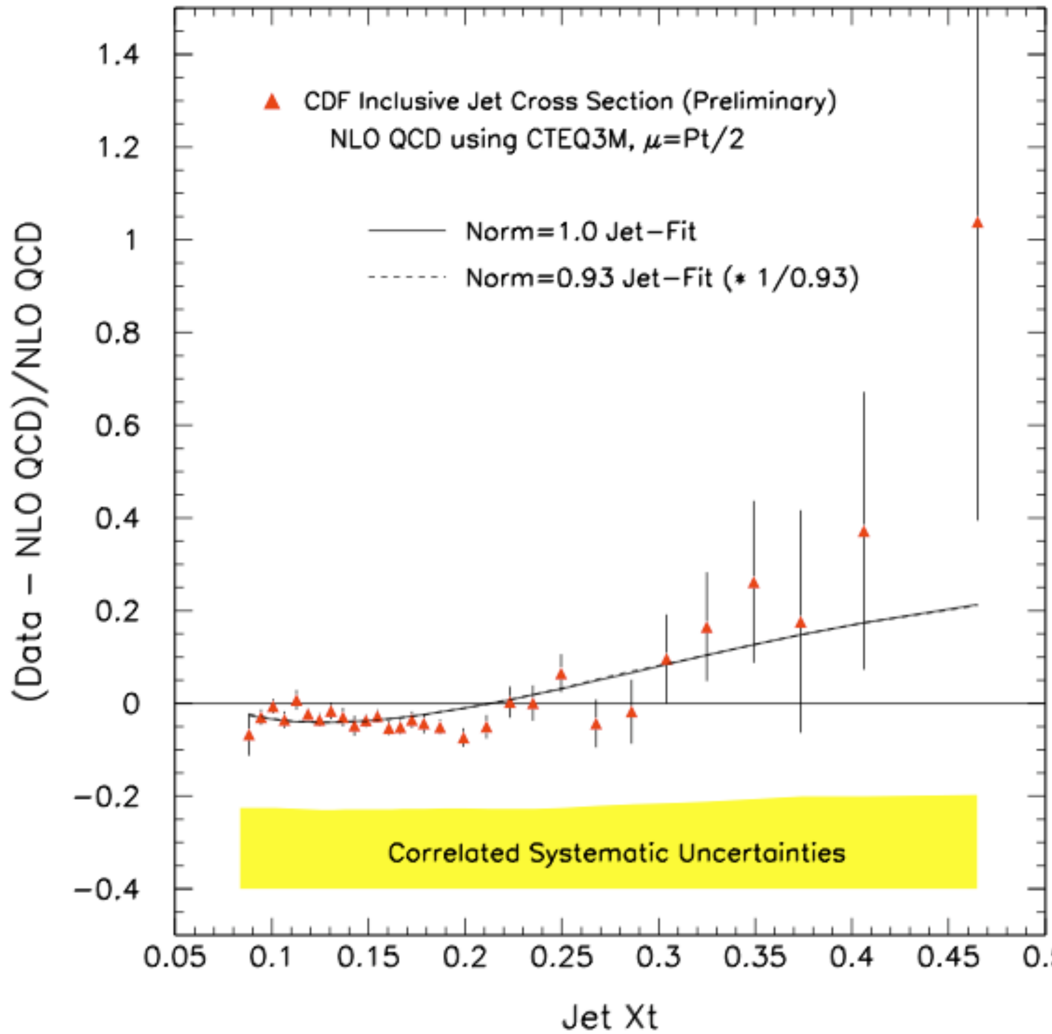


Figure 1: The preliminary CDF jet data is compared to a NLO QCD calculation using the conventional CTEQ3M parton distributions (points), and the new parton distributions fit to the jet data (solid and dashed lines that lie on top of each other).

Jet production: angular distributions

- Much smaller sensitivity to PDFs and JES compared to jet E_t or dijet mass

$$\chi_{dijet} = e^{|y_1 - y_2|}$$

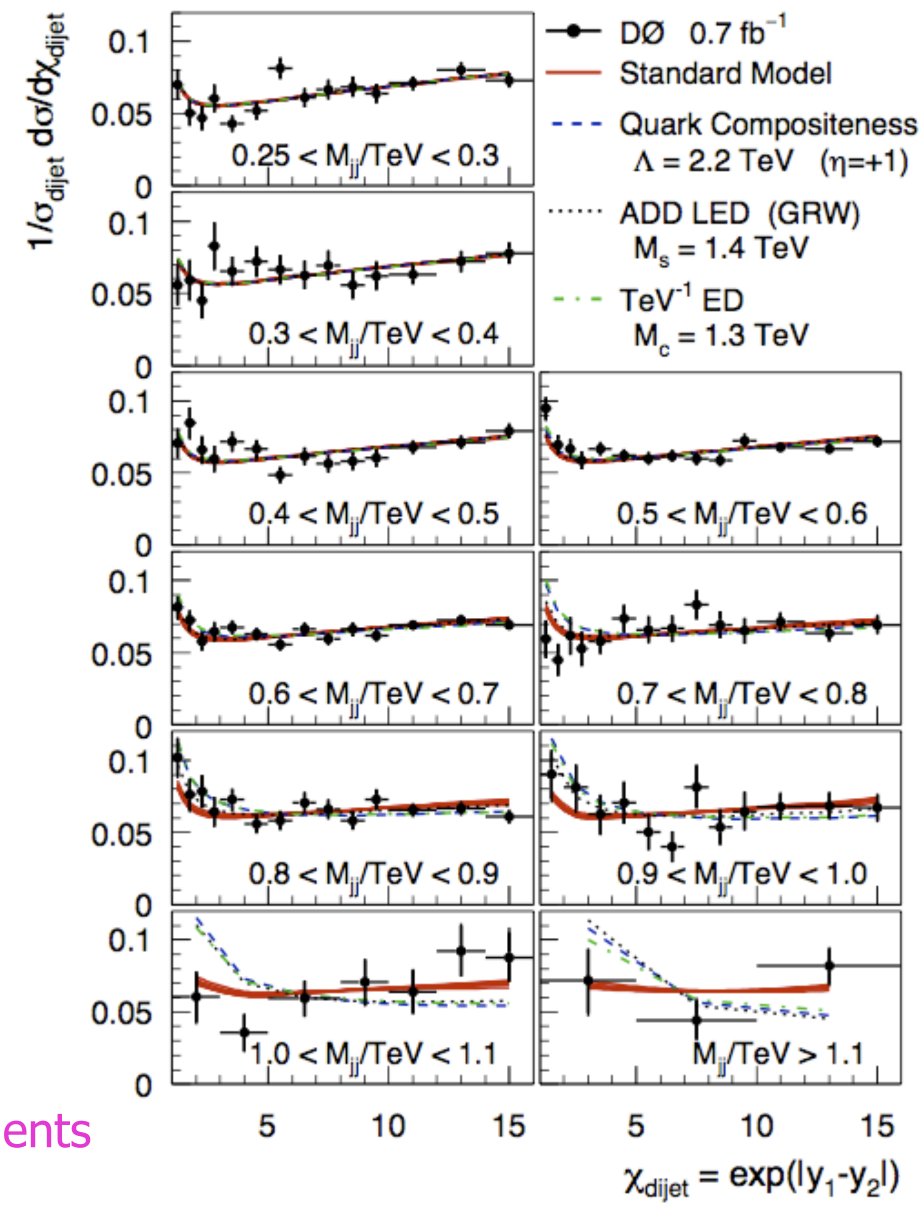
or, in more familiar variables

$$\chi_{dijet} = \frac{1+\cos\theta^*}{1-\cos\theta^*}$$

where θ^* is the polar scattering angle in the c.o.m system

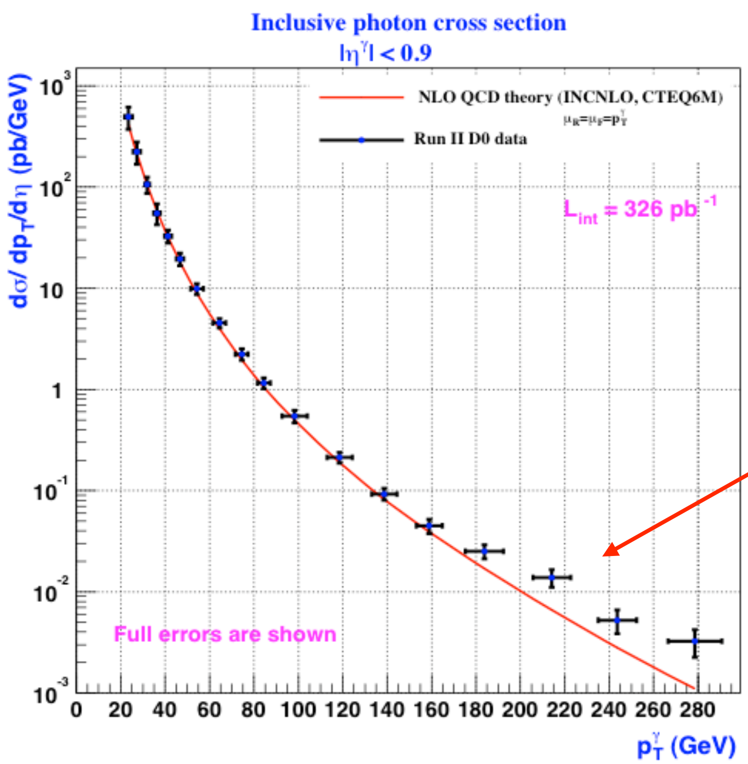
very good variable since for Rutherford scattering the amplitude is χ_{dijet} invariant

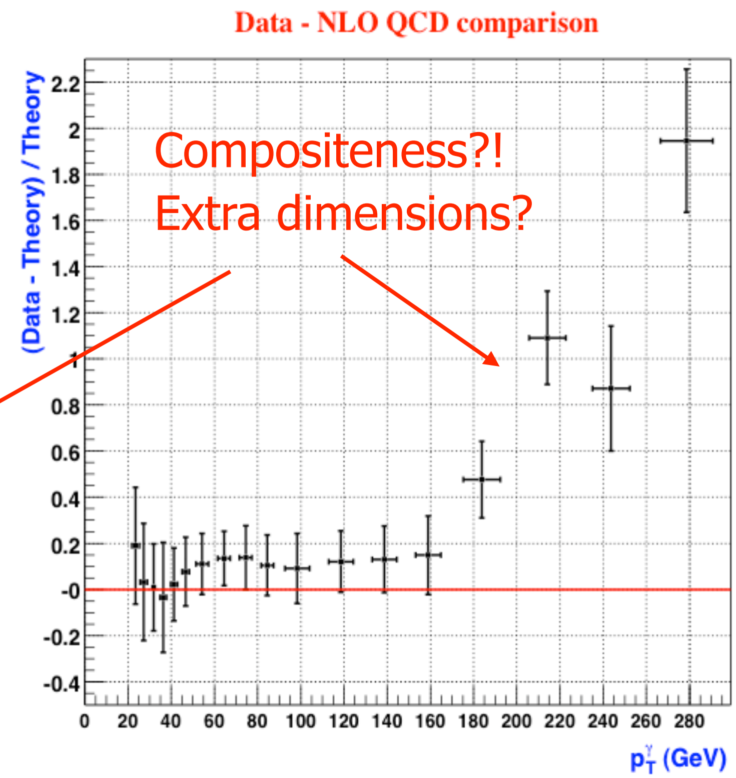
Best limits on Large Extra Dimentions and compositeness come from these measurements



QCD Direct Photon production

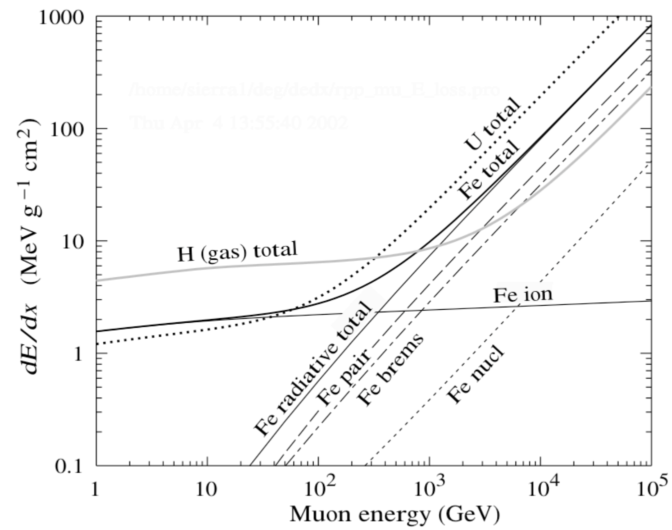
- "Discovery" at DØ: inclusive photon production
  - (Never made it out of the collaboration, though)
  - Select events with high E_T photons, determine purity, extract cross-section and compare with theory, and…

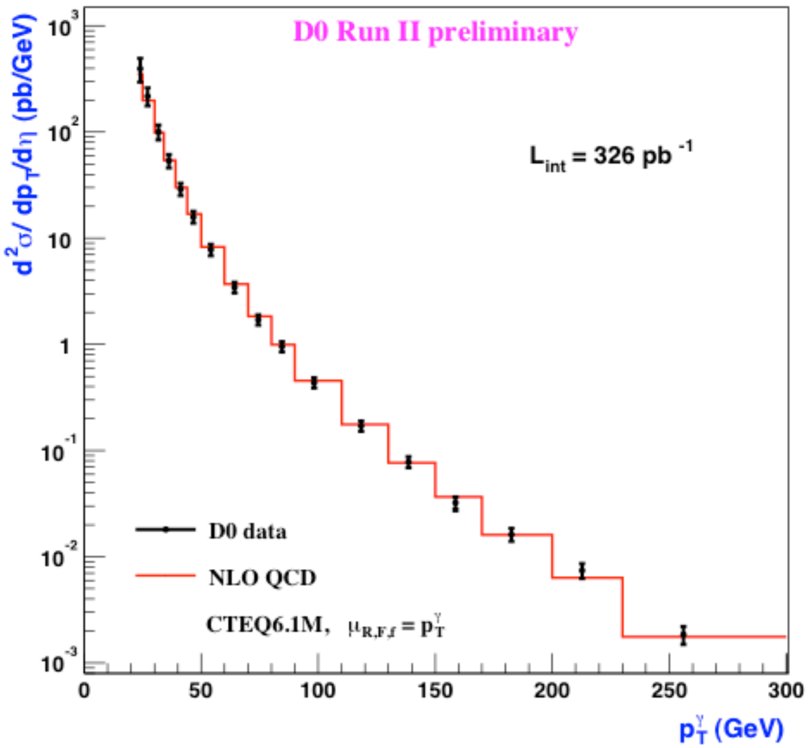


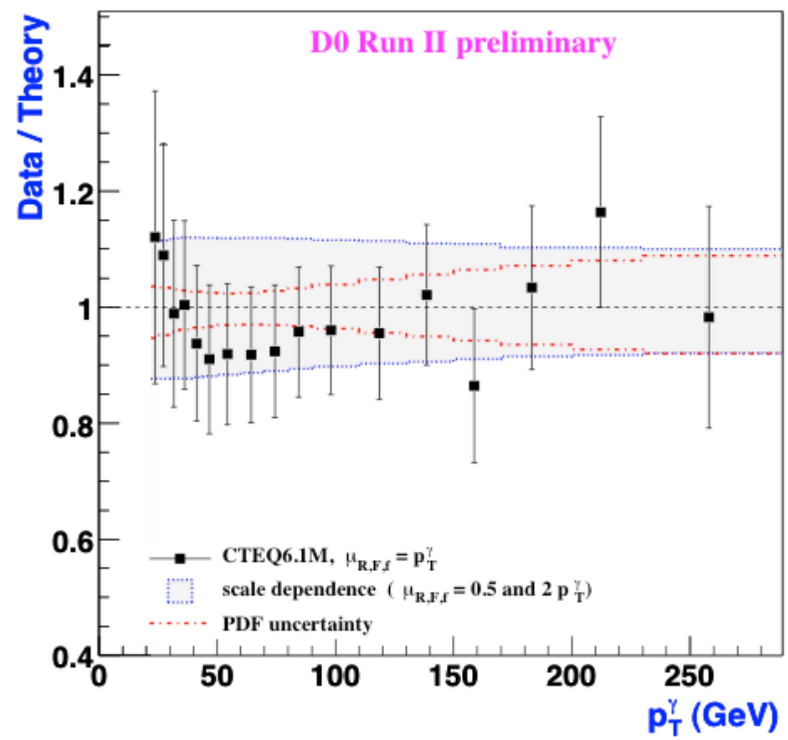


Cosmic Rays and Beam Halo!

- Real muons undergo bremstrahlung in the calorimeter
  - leads to unbalanced events
- Requiring that the events not have large missing E_T gets rid of all the background

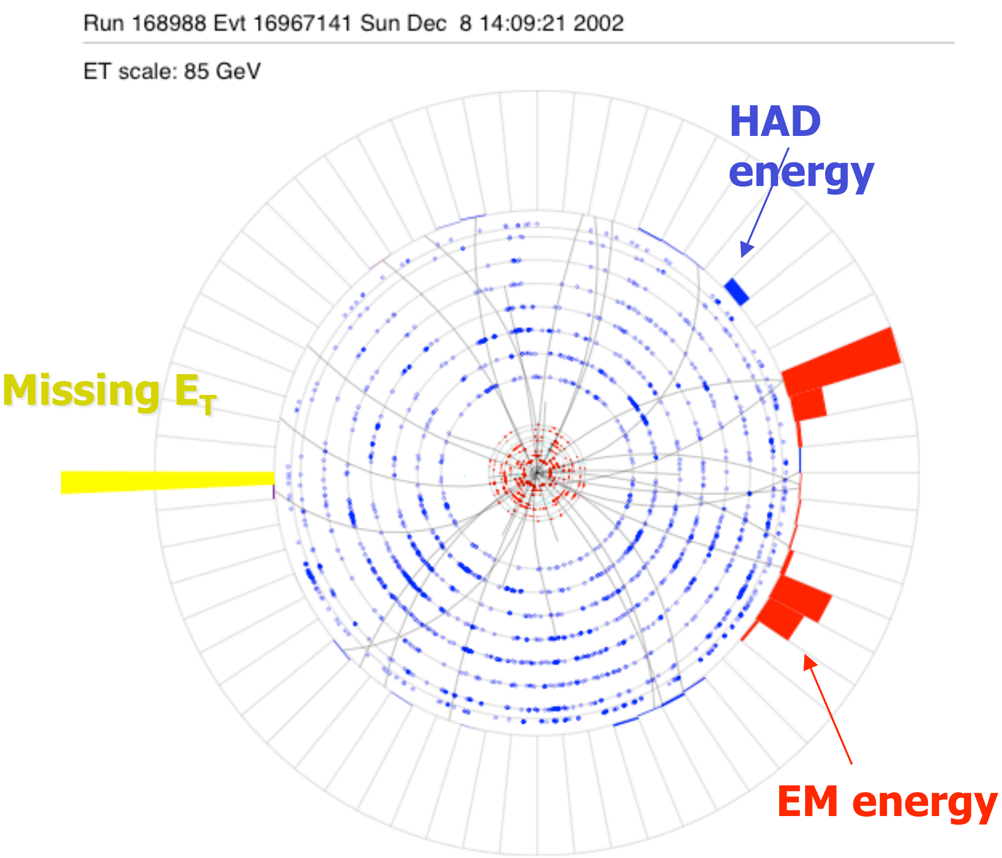






Di-Photons

- Muon can brem more than once…



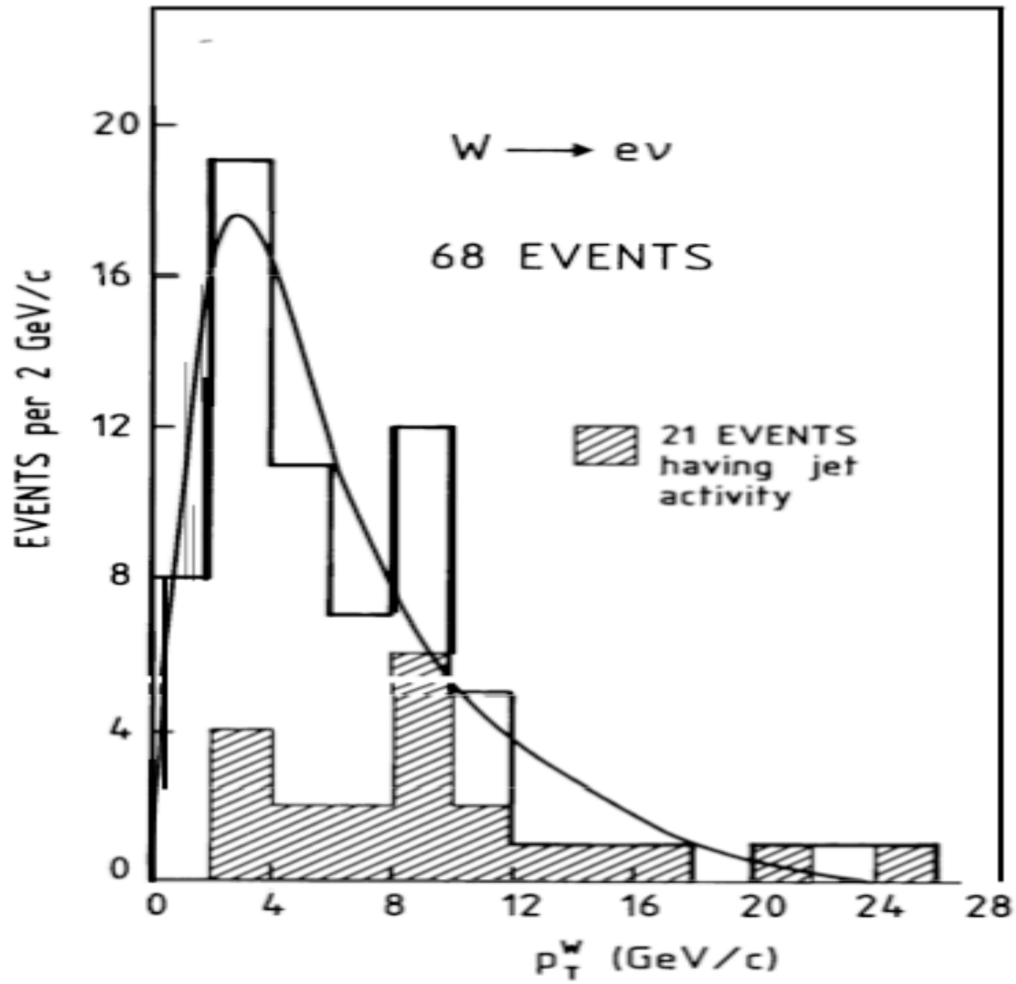
- This is a candidate form $\gamma\gamma$+MET GMSB SUSY search

A Lesson on Discoveries

- At the LHC new physics could become accessible almost instantly – and we will be looking for it. But if a year passes and there are still only upper limit -
- All of Tevatron’s (true) discoveries and important results happened a long way into the run, so remember Lesson 1

patience!

From Noble Prize winning discovery to unglamorous QCD: vector bosons + jets

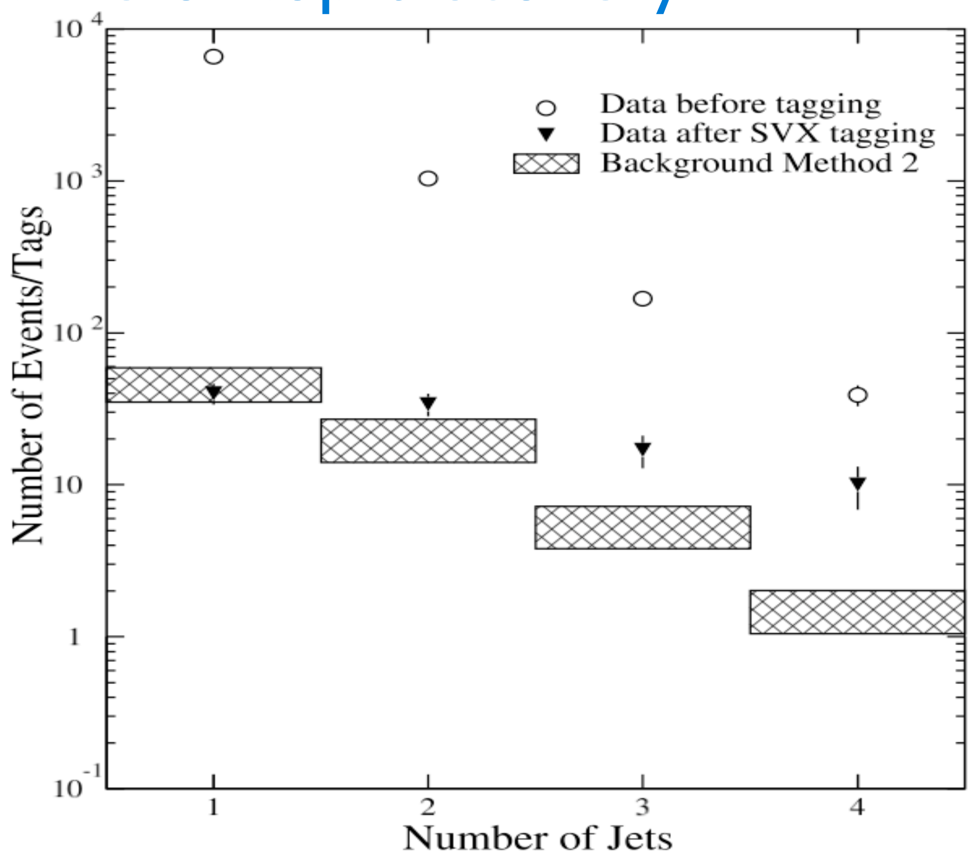


From Noble Prize winning discovery to unglamorous QCD: vector bosons + jets

- State of the art at the time of top discovery – Berend's scaling

MC predictions (i.e. VECBOS) were considered and discarded due to large uncertainties

W+b background prediction used several "conservative" assumptions on heavy flavor production in W+jets compared to multi-jet events and Njet scaling



Closer Look at Hadron Collisions

A cross section is convolution of Matrix Element and PDFs

Physical cross section

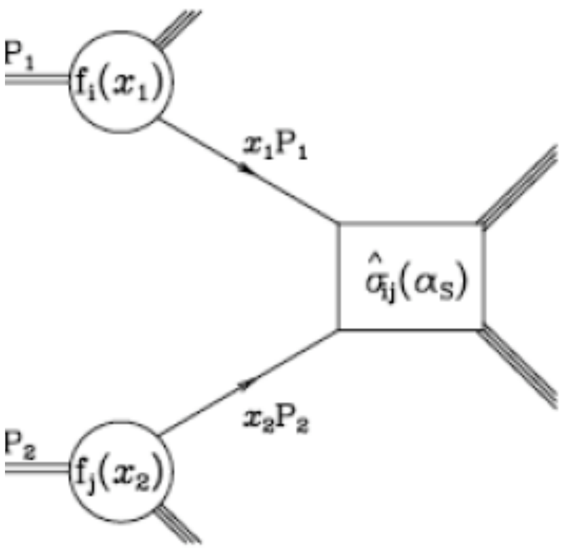
Parton distribution function

Renormalization scale μ_R

$$\sigma(P_1,P_2)=\sum_{i,j}\int dx_1 dx_2\; f_i(x_1,\mu_F) f_j(x_2,\mu_F)\; \hat{\sigma}_{ij}(p_1,p_2,\alpha_S(\mu_R),Q^2,\mu_R,\mu_F).$$

Factorization scale μ_F

Short distance cross section, calculated as a perturbation series in α_S



- Calculations are done in perturbative QCD
  - Possible due to factorization of hard ME and PDF's
    - Can be treated independently
  - Strong coupling (α_s) is large
    - Higher orders needed
    - Calculations complicated
- The hardest question is how to merge soft radiation from ISR with matrix element jet – i.e. junction of perturbative and non-perturbative QCD

W/Z + jets

- top signal @ Tevatron has fairly large S/B
- for electroweak (a.k.a single) top production and low mass Higgs searches S/B is much, much smaller
  - can not proceed before establishing precision understanding of W/Z + jets

“state of the art” description

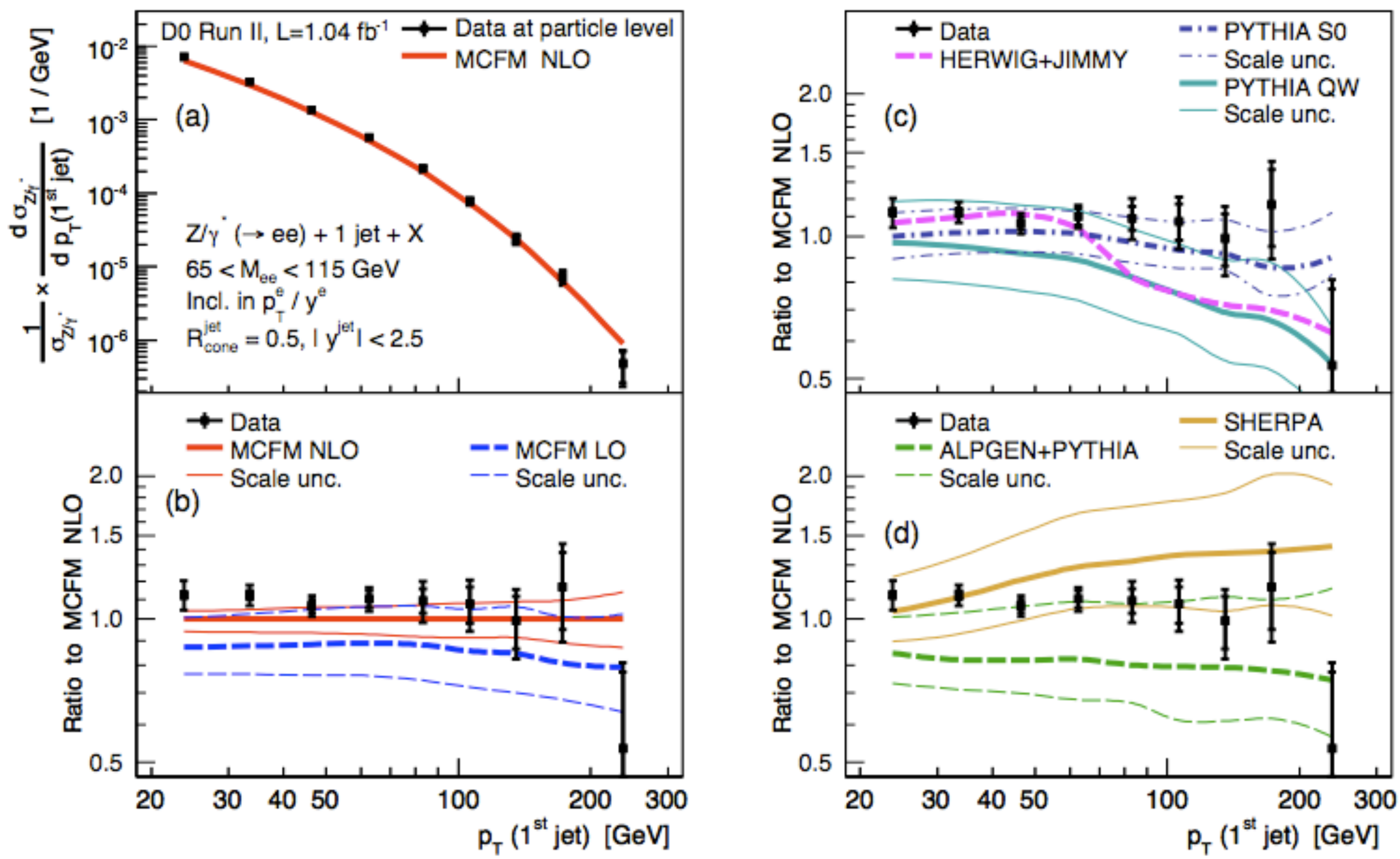


FIG. 1: (a) The measured distribution of $\frac{1}{\sigma_{Z/\gamma^*}} \times \frac{d\sigma}{dp_T(\text{jet})}$ for the leading jet in Z/γ^*+jet+X events, compared to the predictions of MCFM NLO. The ratios of data and theory predictions to MCFM NLO are shown (b) for pQCD predictions corrected to the particle level, (c) for three parton-shower event generator models, and (d) for two event generators matching matrix-elements to a parton shower. The scale uncertainties were evaluated by varying the factorization and renormalization scales by a factor of two.

"state of the art" description

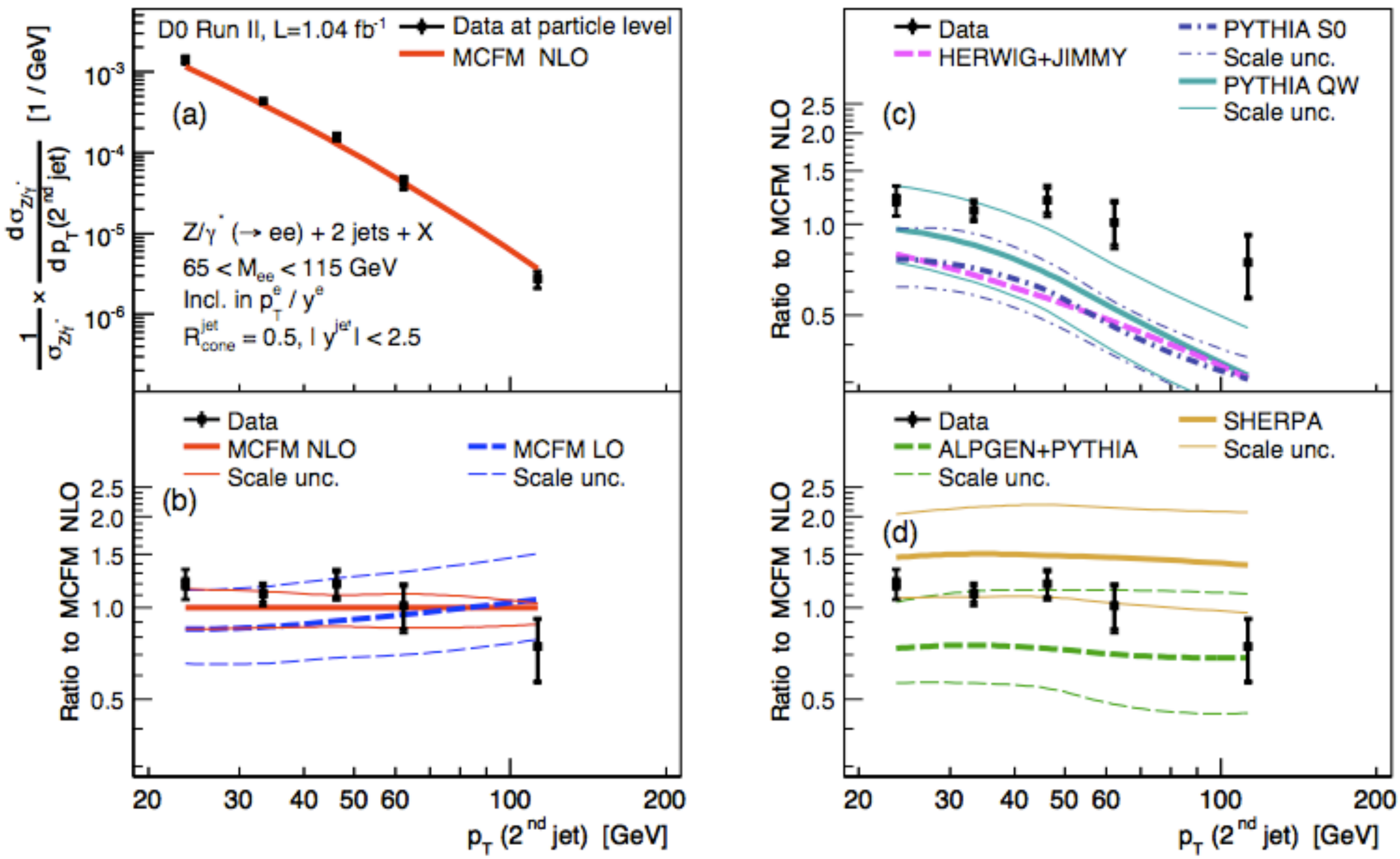


FIG. 2: (a) The measured distribution of $\frac{1}{\sigma_{Z/\gamma^*}} \times \frac{d\sigma}{dp_T(\text{jet})}$ for the second jet in $Z/\gamma^* + 2$ jets$+X$ events, compared to the predictions of MCFM NLO. The ratios of data and theory predictions to MCFM NLO are shown (b) for pQCD predictions corrected to the particle level, (c) for three parton-shower event generator models, and (d) for two event generators matching matrix-elements to a parton shower. The scale uncertainties were evaluated by varying the factorization and renormalization scales by a factor of two.

"state of the art" description

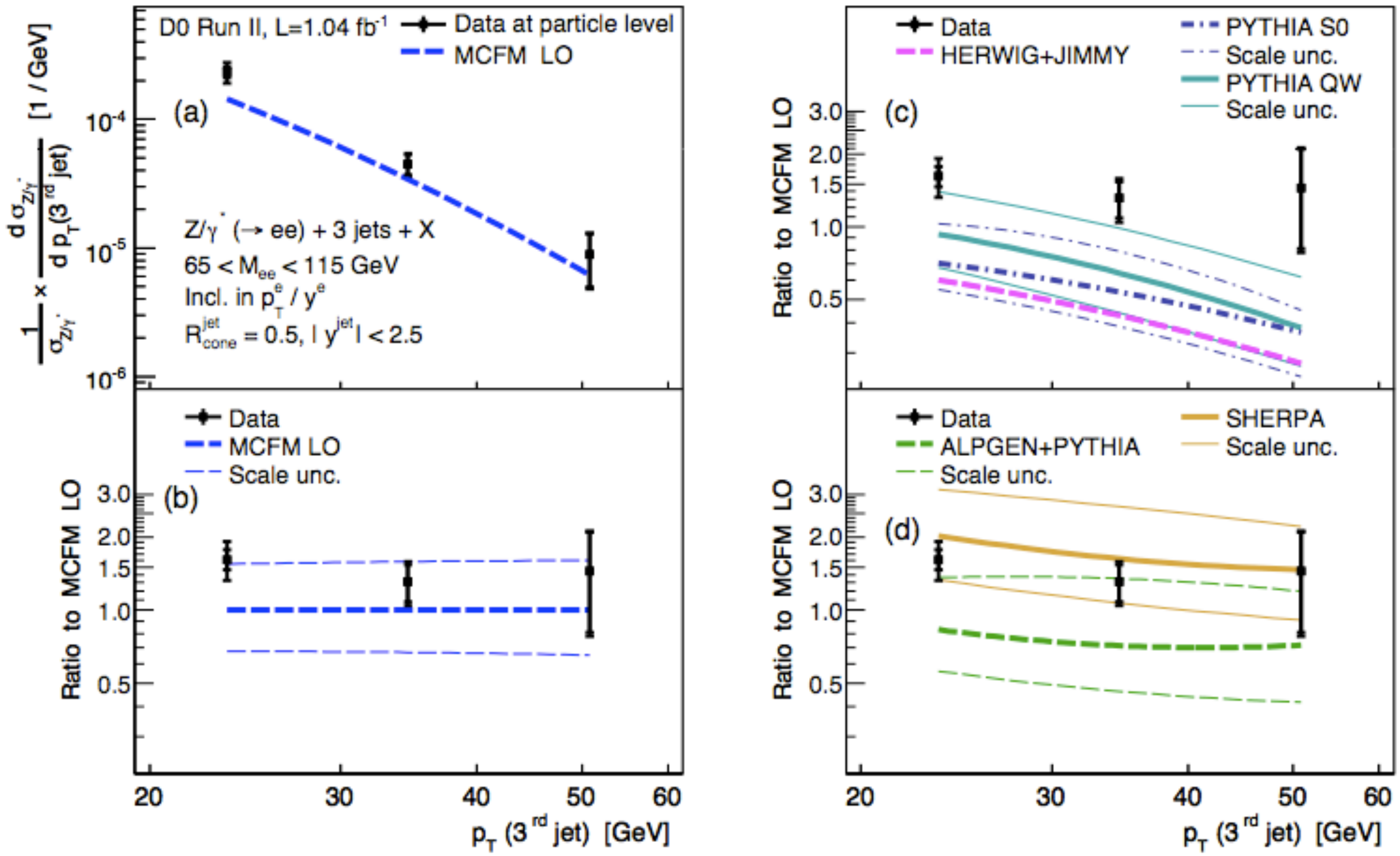


FIG. 3: (a) The measured distribution of $\frac{1}{\sigma_{Z/\gamma^*}} \times \frac{d\sigma}{dp_T(\text{jet})}$ for the third jet in Z/γ^*+3 jets+X events, compared to the predictions of MCFM LO. The ratios of data and theory predictions to MCFM NLO are shown (b) for pQCD predictions corrected to the particle level, (c) for three parton-shower event generator models, and (d) for two event generators matching matrix-elements to a parton shower. The scale uncertainties were evaluated by varying the factorization and renormalization scales by a factor of two.

“state of the art” description

- Good news: NLO calculation is not far off
- Bad news: event generators are very far off

- Strategy for single top and Higgs searches at the Tevatron:
  - generate MC (i.e. ALPGEN) in jet bins
  - determine per jet multiplicity and flavor bin corrections for number of events, and Z p_T
  - Use W/Z mass difference and MC to translate those into parameters for W re-weighting

“state of the art” description

Food for thought:

- the fact that W has a “twin” makes it possible to estimate the kinematics of its production (modulo PDF’s differences of up and down quarks)

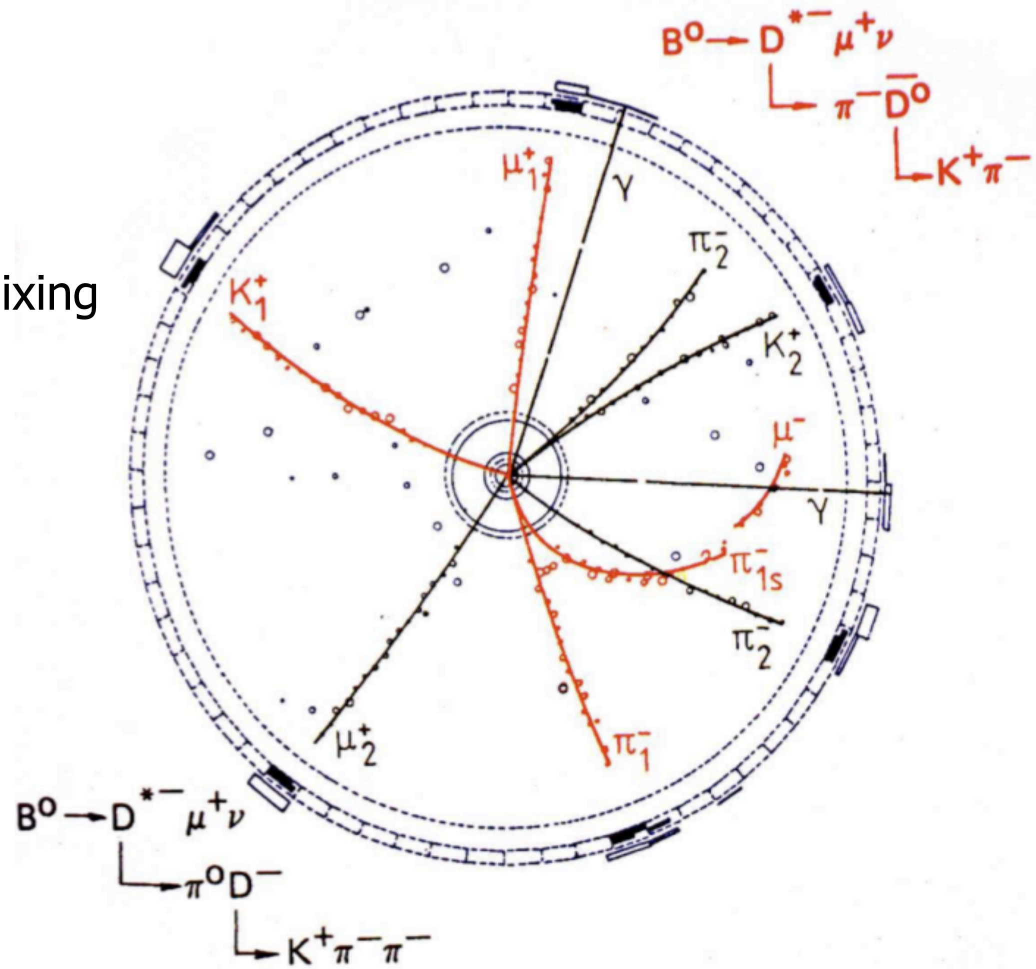
- top has no “twin” and is produced mostly from gg at the LHC. So copiously, that it is the main background to almost everything.

Flavor at the Tevatron

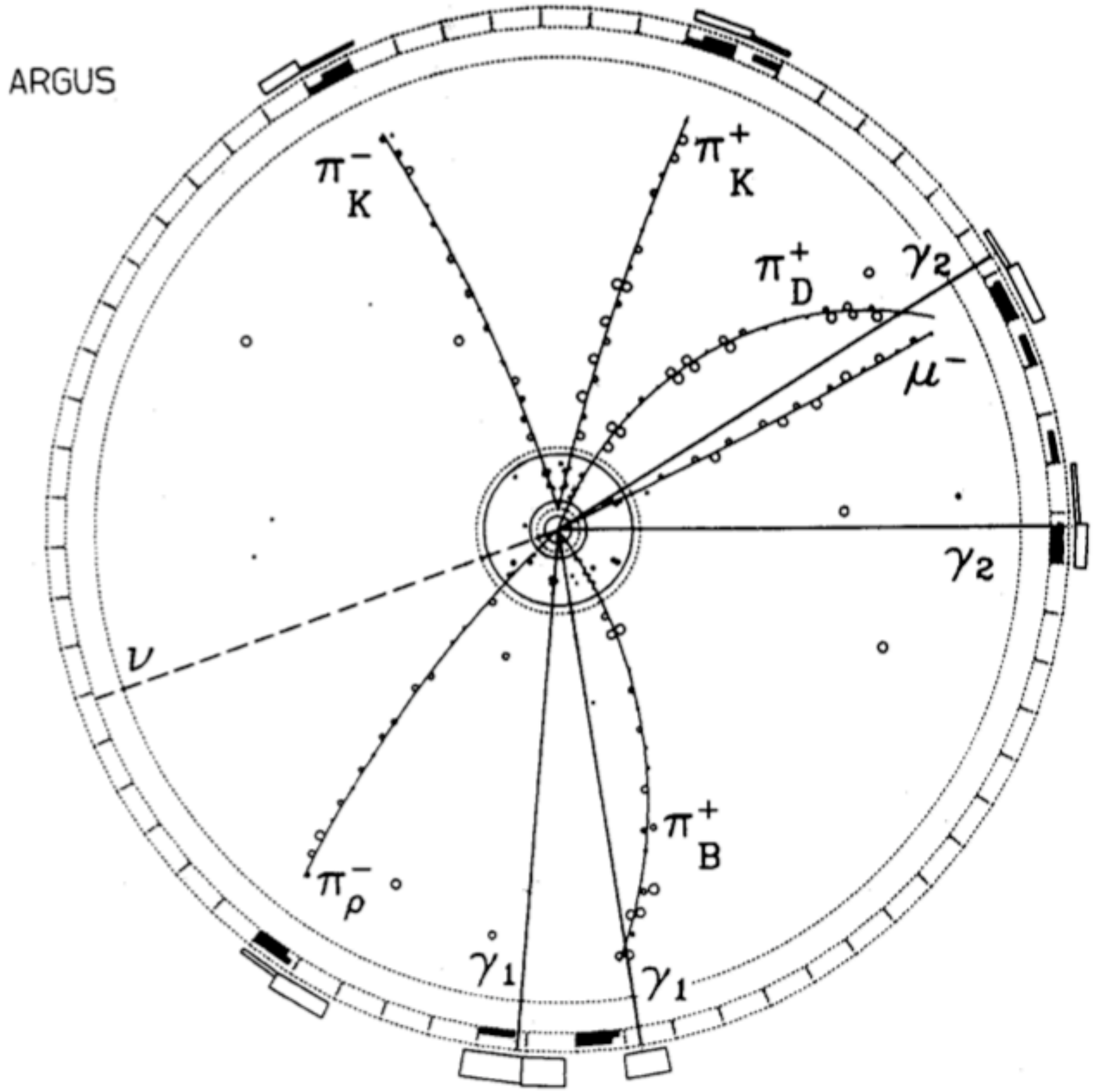
- Before 90-ies bottom/charm physics was done almost exclusively in e^+e^- environment

ARGUS

discovery of large B_d mixing



Power of One Event



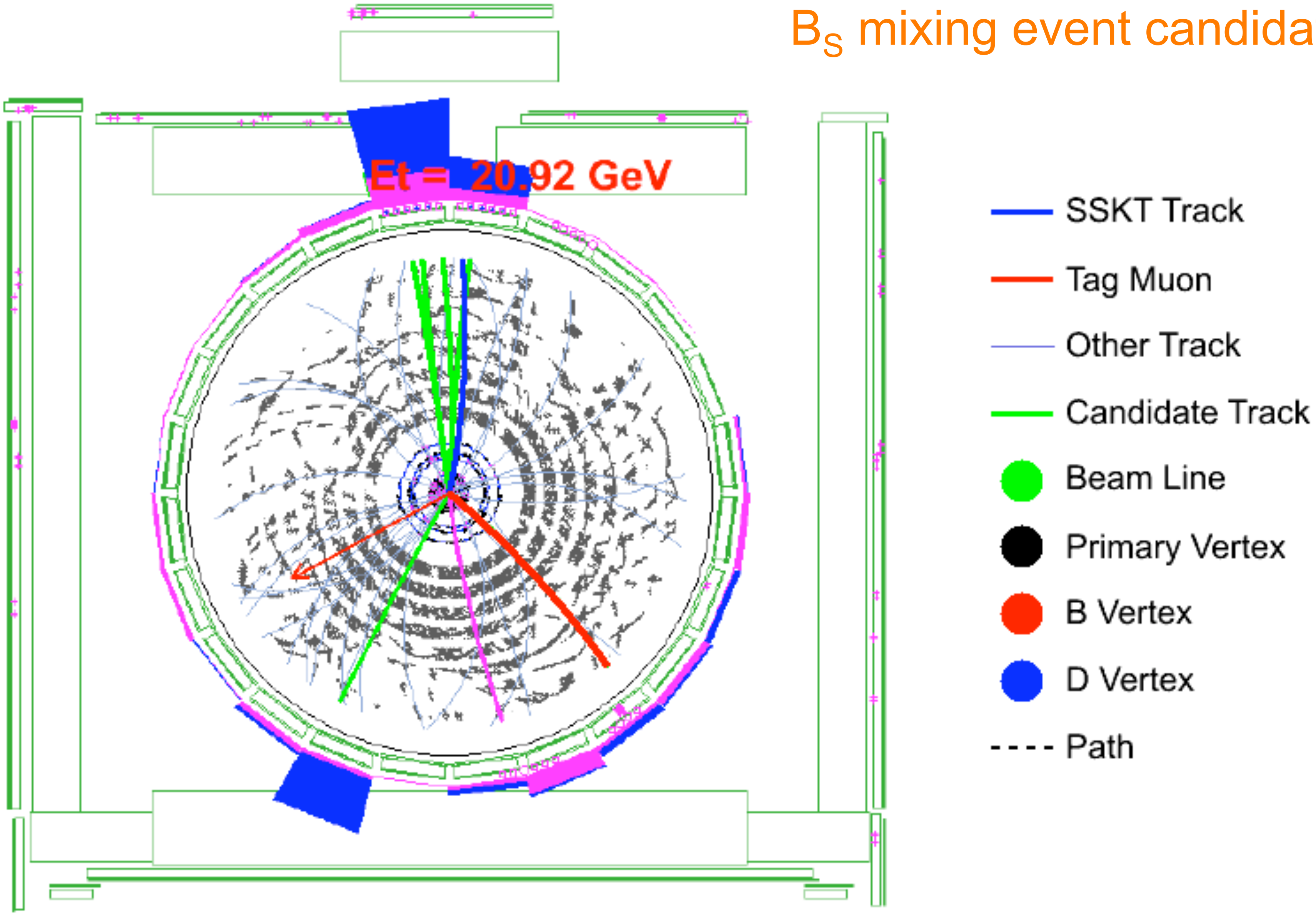
$\Upsilon 4S \rightarrow B^0 \bar{B}^0$
$\hookrightarrow \bar{B}^0$

$\bar{B}^0 \rightarrow D^{*+} \rho^-$
$\hookrightarrow \pi^-_\rho \pi^0$
$\hookrightarrow \gamma_1 \gamma_1$
$\hookrightarrow D^0 \pi^+_D$
$\hookrightarrow \bar{K}^0 \pi^0$
$\hookrightarrow \gamma_2 \gamma_2$
$\hookrightarrow \pi^+_K \pi^-_K$

$\bar{B}^0 \rightarrow \mu^- \pi^+_B \nu$

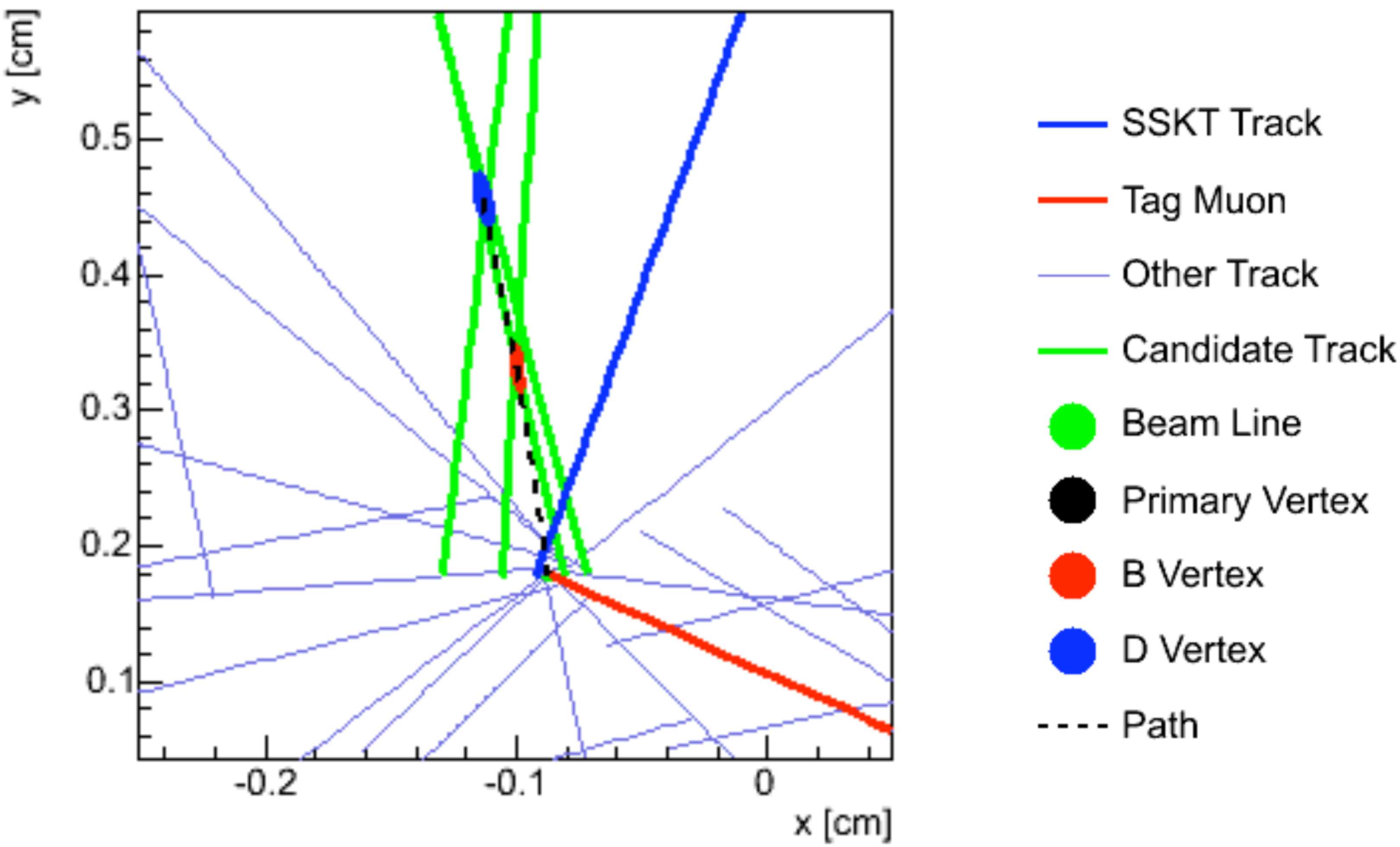
Power of One Event

B_s mixing event candidate



Power of One Event

B_S mixing event candidate



Flavor at the Tevatron

And yet it is possible to do amazing physics!

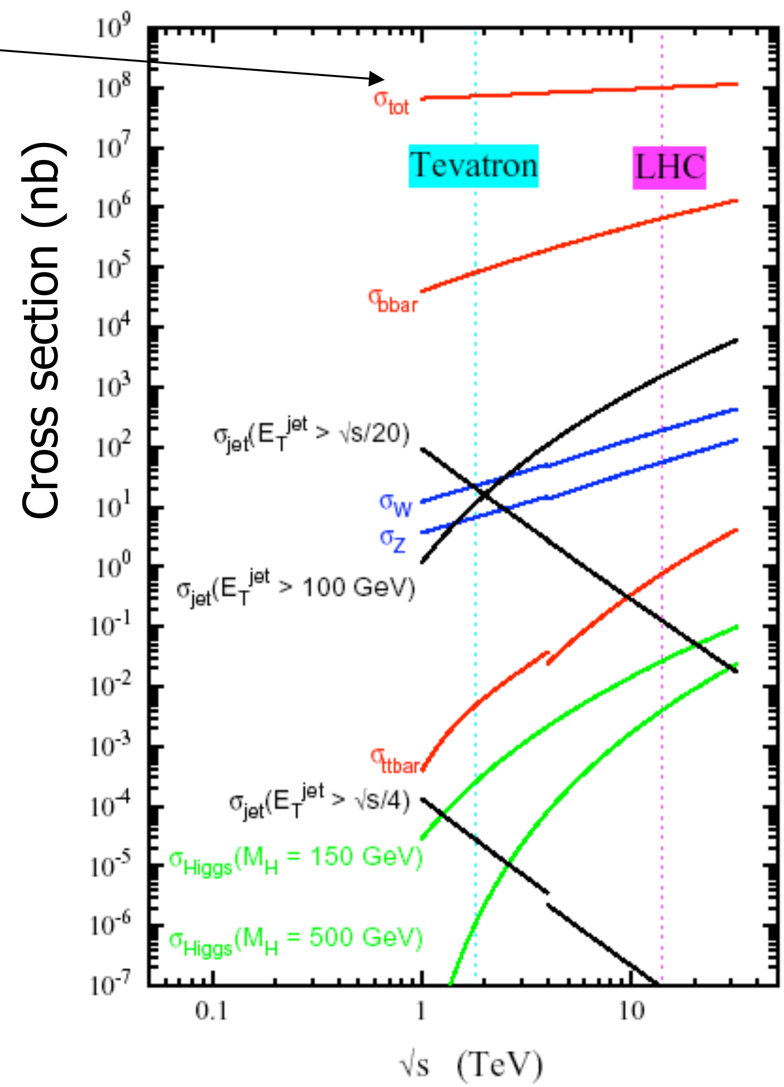
- Spectroscopy
  - B_c, excited B/B_S states, exotic charm states, …
- CP violation
- BB mixing
  - discovery of B_S mixing
- DD mixing

But before we dive into physics – more of experimental prose:

TRIGGER

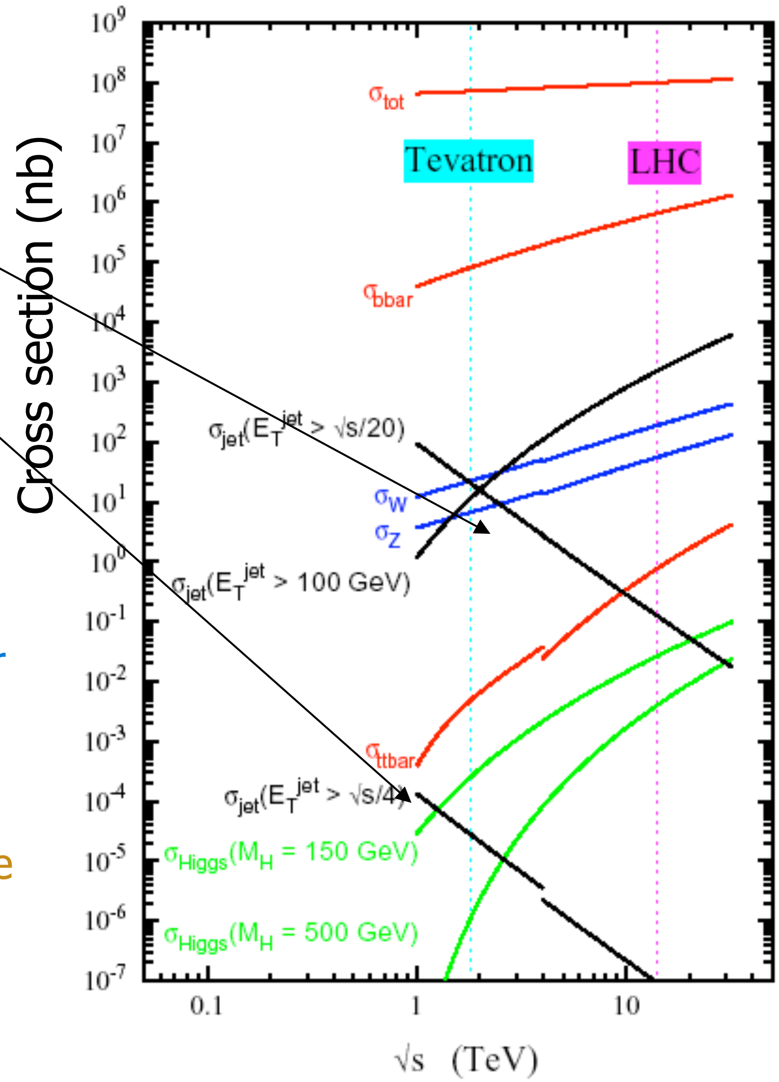
Trigger: Selecting the interesting events (I)

- Our starting point is here
  - At the LHC the rate for all collisions is 40MHz!
  - Although ideal, it's impossible to keep all the events
- Need to decide a priori which are the "interesting" events to keep/filter
- Need to be selective
  - enhance rare processes
  - reduce common ones
- If we make bad/unwise choices we will throw away the new physics!
  - If you don't trigger on it, it's gone forever!
- Theory plays a role in guiding these choices
  - Important to have good communication between theorists and experimentalists for coming up with new triggers



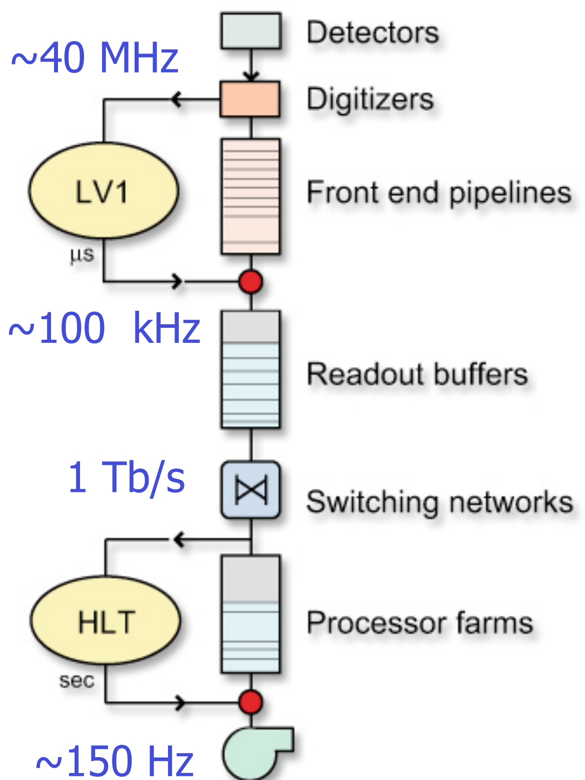
Trigger: Selecting the interesting events (II)

- We want to trigger on things that are rare in the SM
- But also want to keep "less" interesting events (at least initially) for standard-candle measurements, calibrations, etc.
- Your "run-of-the-mill" trigger table will contain triggers on:
  - electroweak particles: γ , e, τ at as low an energy as possible
  - very high-energy partons (jets)
  - apparent invisible particles (MET)
- Beware!
  - All measurements are distorted by the trigger
  - Any measurement must account for the efficiency of the trigger and the resulting distortion (eta, phi pt dependence?)
- Therefore, we must measure the efficiencies of the interesting triggers
  - "Backup" triggers are often needed

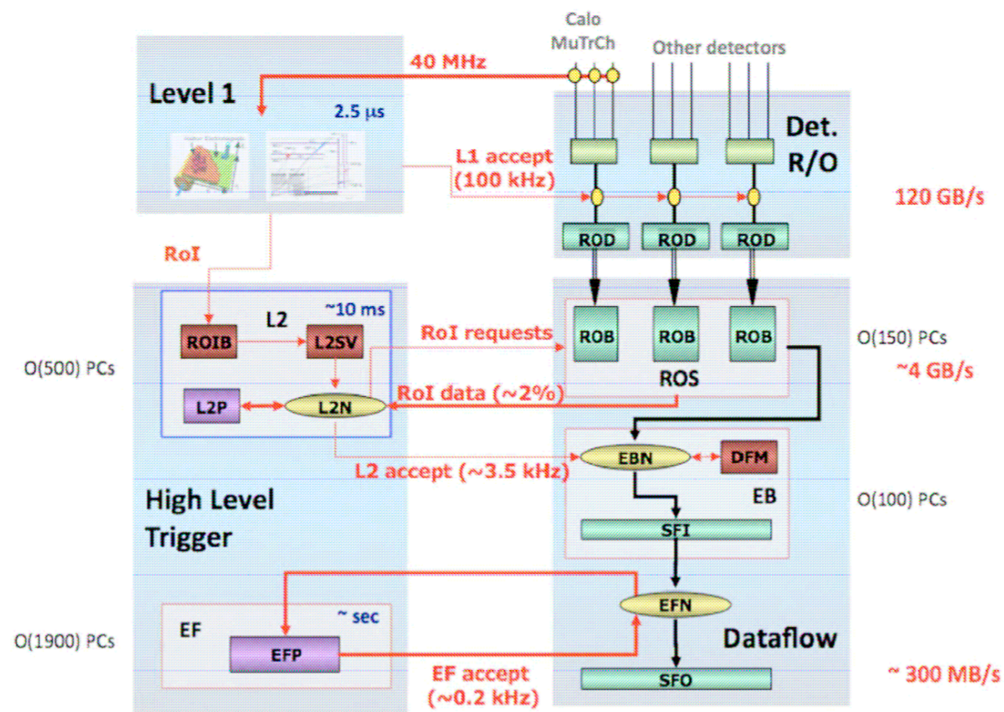


CMS and ATLAS Triggers

CMS



ATLAS



Level 1: Hardware based (electronics)

Level 2: Software based

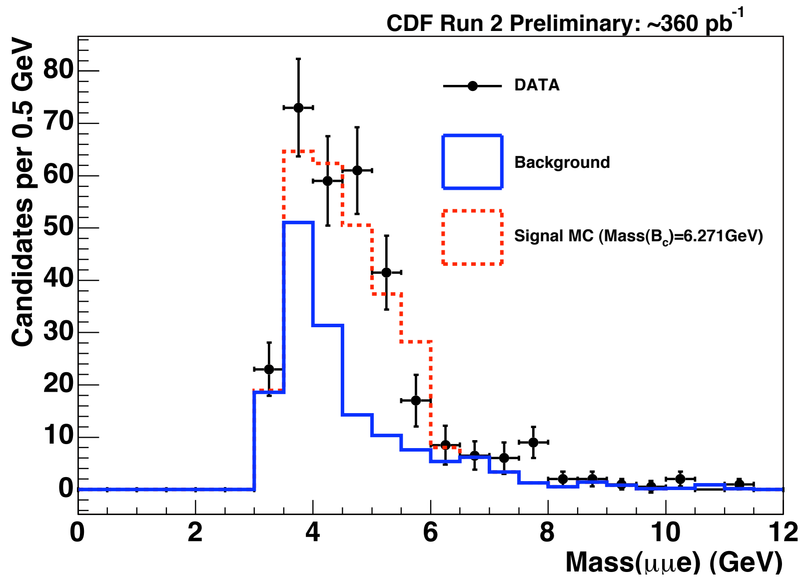
The decision to keep ~1/200,000 events happens every second.

No room for mistakes!

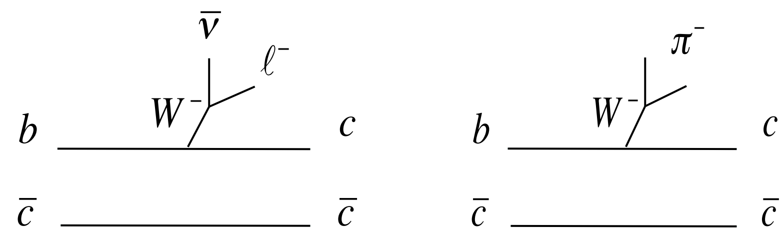
Tevatron Triggers for flavor physics

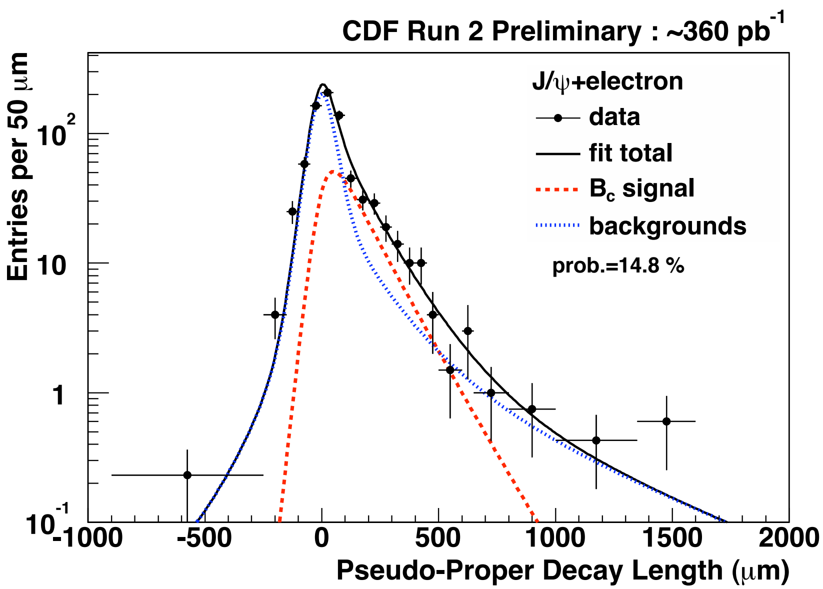
- Level 1: limited options
  - one or two low p_T muons (trigger threshold is the key)
  - two tracks (CDF only)
- Level 2:
  - silicon IP information
- Level 3:
  - particle combinations, mass windows, etc…

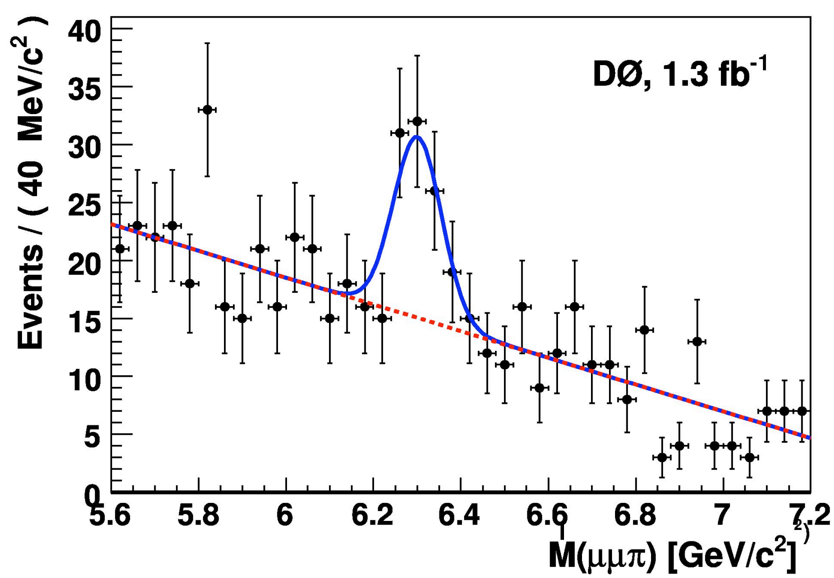
Spectroscopy: B_C



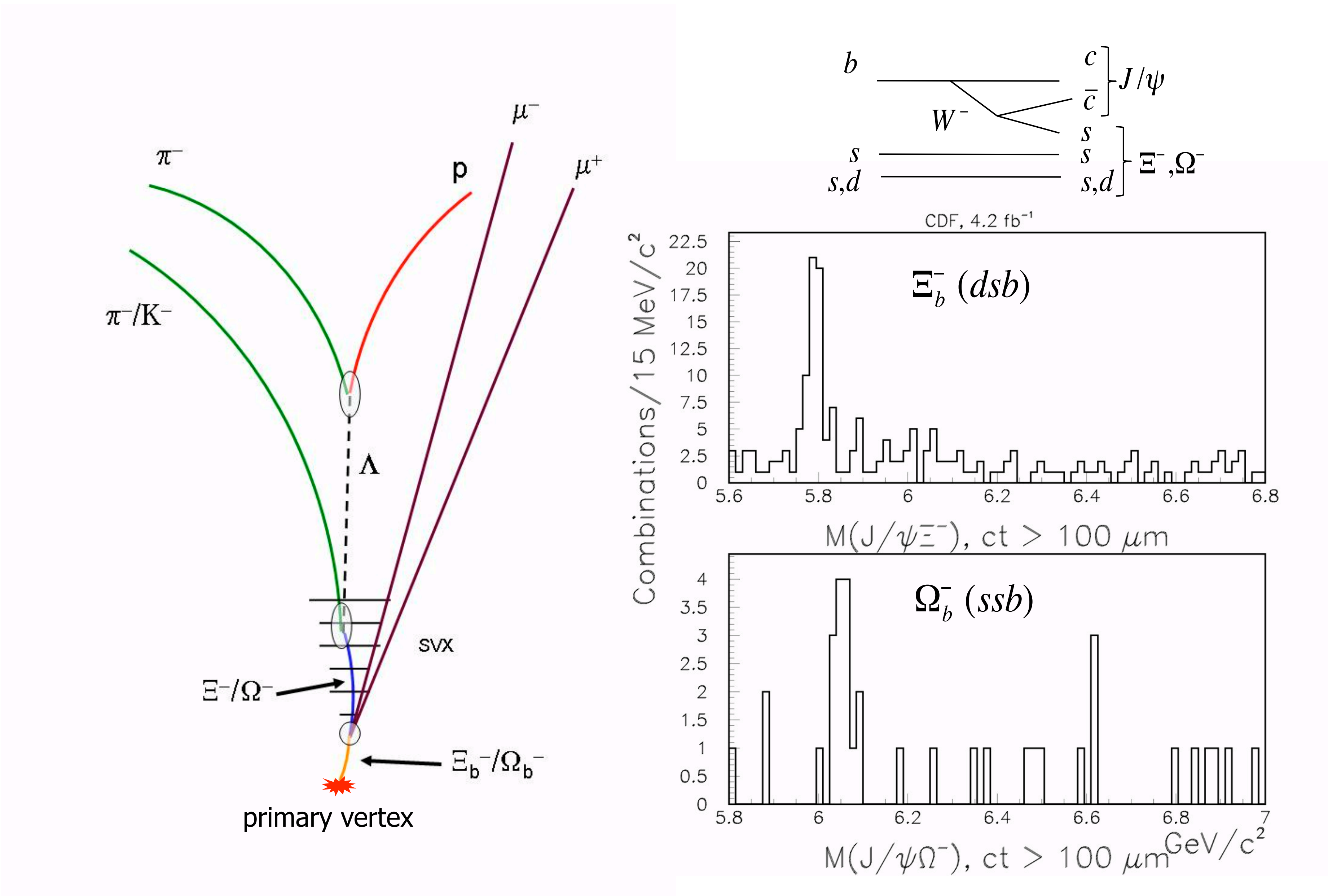
- two heavy quarks, with same order lifetimes





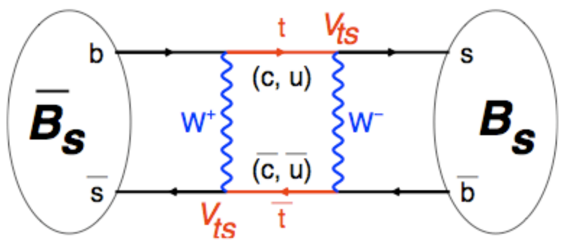


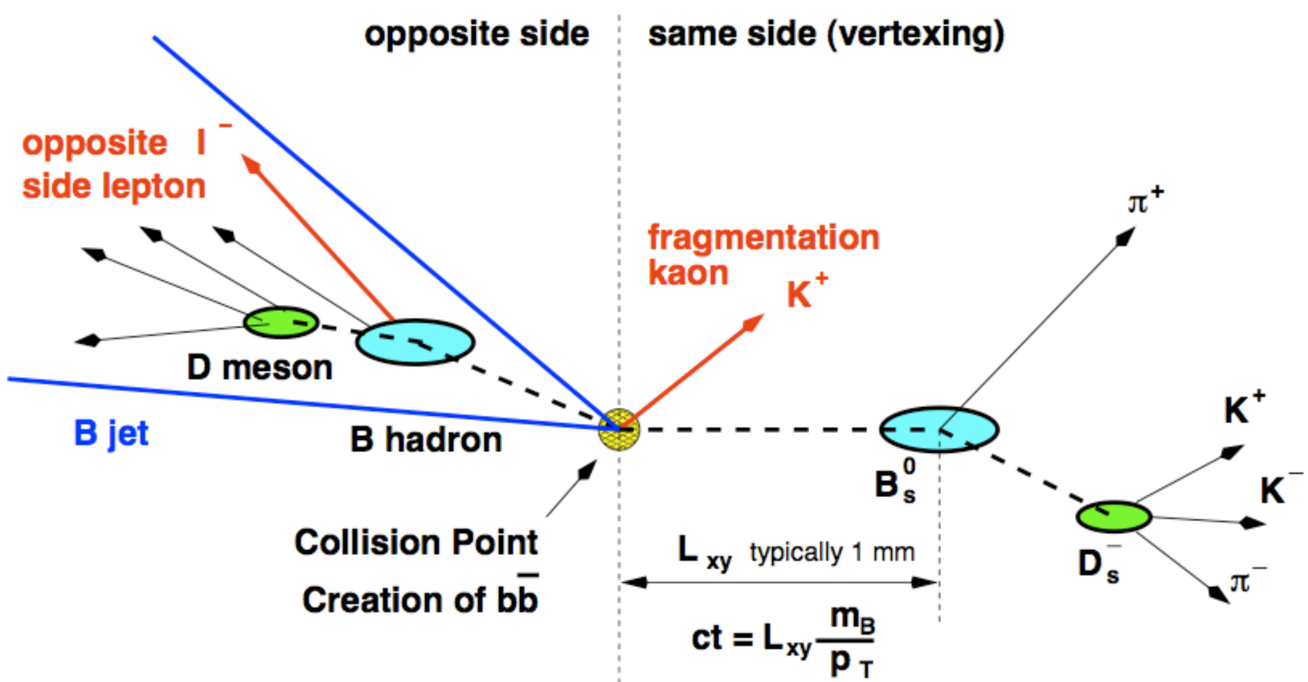
Spectroscopy: Baryons



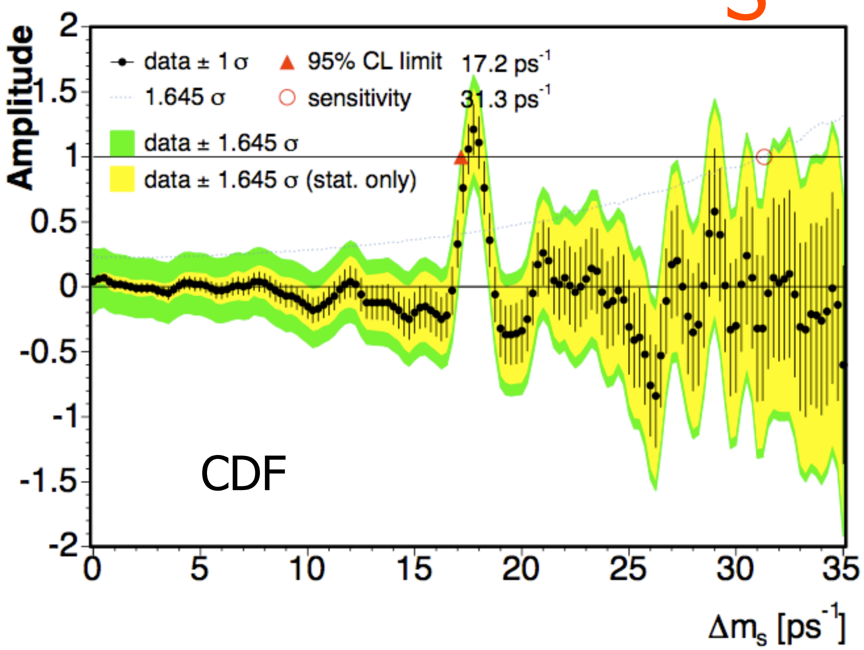
B_s mixing

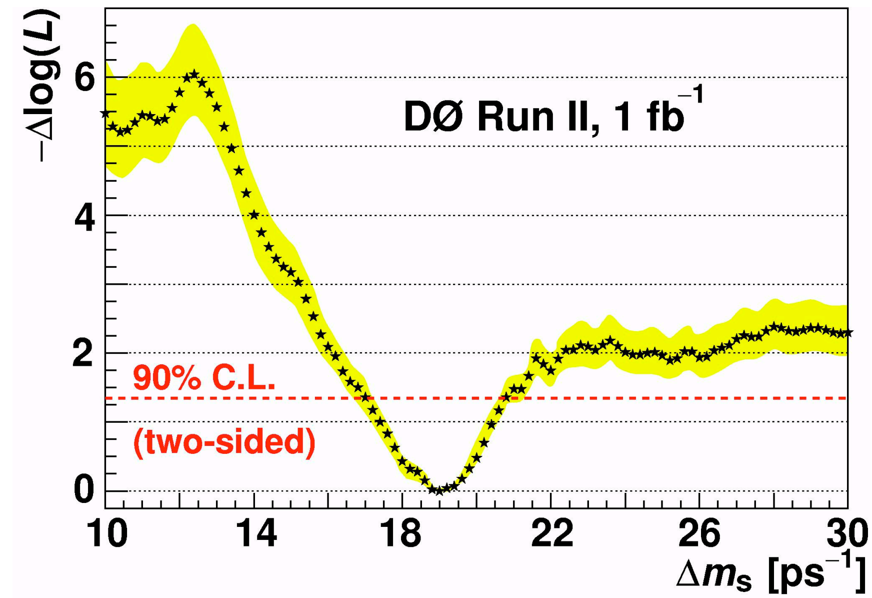
- Gives access to V_{ts} and sensitive to new particles in the loop
- Interference between $B_{d,s} \to \overline{B}_{d,s} \to X_{CP}$ and $B_{d,s} \to X_{CP}$ provides a window to CP violation





B_S mixing

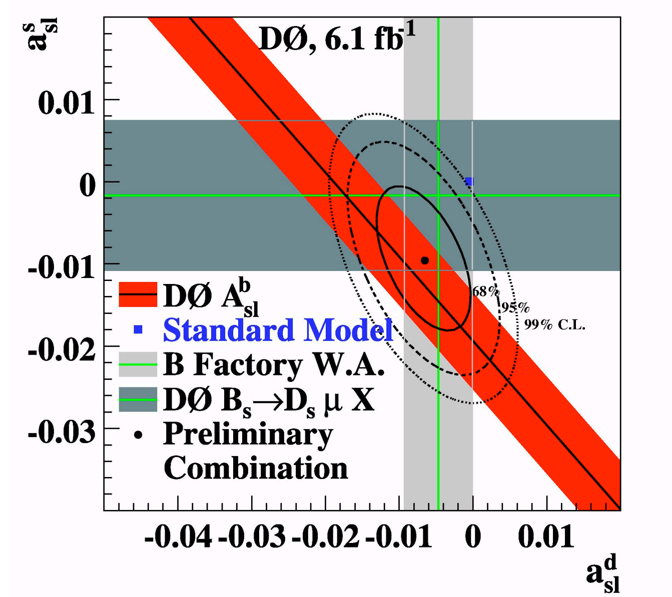




- Recent DØ result – deviation from SM prediction of dilepton charge assymetry: more $\mu^+\mu^+$ pairs are produced compared to $\mu^-\mu^-$

$$A^b_{\rm sl} = -0.00957 \pm 0.00251\ ({\rm stat}) \pm 0.00146\ ({\rm syst})$$

$$A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$



Summary of lessons so far

- LHC will be a 20-30 year program. Be patient!
  - although the delays affected careers of young people and are generally quite frustrating
- Hadron colliders are very messy (but the way to get to the energy frontier)
  - underlying event
  - large occupancies
  - huge total cross-sections – pile-up
  - trigger shapes everything
- Yet, it is possible to do precision measurements!